US009713302B2

(12) **United States Patent**
Sandin et al.

(10) **Patent No.: US 9,713,302 B2**
(45) **Date of Patent: Jul. 25, 2017**

(54) **ROBOT CONFINEMENT**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 112 days.

(21) Appl. No.: **14/489,847**

(22) Filed: **Sep. 18, 2014**

(65) **Prior Publication Data**

US 2015/0006015 A1 Jan. 1, 2015

Related U.S. Application Data

(63) Continuation of application No. 11/688,213, filed on Mar. 19, 2007, now Pat. No. 8,868,237.
(Continued)

(51) **Int. Cl.**

G05D 1/02	(2006.01)
A01D 34/00	(2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***A01D 34/008*** (2013.01); ***B60L 3/0023*** (2013.01); ***B60L 11/126*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC G05D 1/0255; G05D 1/028; G05D 1/0259; G05D 1/0265; G05D 1/0225;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,751,030 A	6/1956	Null
3,128,840 A	4/1964	Barrett

(Continued)

FOREIGN PATENT DOCUMENTS

DE	19932552	2/2000
EP	0774702	5/1997

(Continued)

OTHER PUBLICATIONS

Caracciolo et al., "Trajectory Tracking Control of a Four-wheel Differentially Driven Mobile Robot," IEEE Int. Conf. Robotics and Automation, Detroit, MI, 1999, pp. 2632-2638.
(Continued)

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(57) **ABSTRACT**

An autonomous coverage robot system includes an active boundary responder comprising a wire powered with a modulated current placed along a perimeter of a property, at least one passive boundary responder placed on a property interior circumscribed by the active boundary responder, and an autonomous coverage robot. The robot includes a drive system carried by a body and configured to maneuver the robot across the property interior. The robot includes a signal emitter emitting a signal, where the passive boundary
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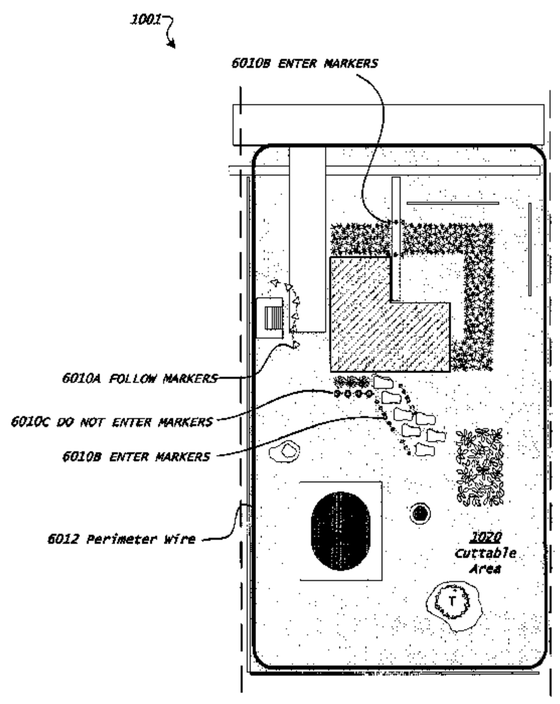

responder is responsive to the signal and a boundary responder detection system carried by the body. The boundary responder detector is configured to redirect the robot both in response to the responder detection system detecting an active boundary responder and in response to detecting a passive boundary responder.

16 Claims, 56 Drawing Sheets

Related U.S. Application Data

(60) Provisional application No. 60/783,268, filed on Mar. 17, 2006, provisional application No. 60/865,069, filed on Nov. 9, 2006, provisional application No. 60/803,030, filed on May 23, 2006.

(51) **Int. Cl.**

B60L 3/00	(2006.01)
B60L 11/12	(2006.01)
B60L 11/18	(2006.01)

(52) **U.S. Cl.**

CPC ***B60L 11/1803*** (2013.01); ***B60L 11/1805*** (2013.01); ***B60L 11/1816*** (2013.01); ***B60L 11/1861*** (2013.01); ***B60L 11/1877*** (2013.01); ***G05D 1/028*** (2013.01); ***G05D 1/0255*** (2013.01); ***G05D 1/0259*** (2013.01); ***G05D 1/0265*** (2013.01); *B60L 2200/40* (2013.01); *B60L 2210/30* (2013.01); *B60L 2210/40* (2013.01); *B60L 2240/36* (2013.01); *B60L 2240/425* (2013.01); *B60L 2240/662* (2013.01); *B60L 2250/16* (2013.01); *B60L 2260/32* (2013.01); *B60L 2270/145* (2013.01); *G05D 1/0225* (2013.01); *G05D 2201/0203* (2013.01); *G05D 2201/0208* (2013.01); *G05D 2201/0215* (2013.01); *Y02T 10/6217* (2013.01); *Y02T 10/642* (2013.01); *Y02T 10/705* (2013.01); *Y02T 10/7005* (2013.01); *Y02T 10/7044* (2013.01); *Y02T 10/7072* (2013.01); *Y02T 10/7077* (2013.01); *Y02T 10/7094* (2013.01); *Y02T 10/7241* (2013.01); *Y02T 10/7291* (2013.01); *Y02T 90/127* (2013.01); *Y02T 90/14* (2013.01); *Y02T 90/16* (2013.01); *Y10S 901/01* (2013.01); *Y10S 901/09* (2013.01)

(58) **Field of Classification Search**

CPC ... G05D 2201/0203; G05D 2201/0208; G05D 2201/0215; Y10S 901/01; Y10S 901/09; A01D 34/008

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,385,041	A	5/1968	Douglas
3,457,575	A	7/1969	Bienek
3,550,714	A	12/1970	Bellinger
3,674,316	A	7/1972	De Brey
3,924,389	A	12/1975	Kita
3,937,174	A	2/1976	Haaga
3,946,543	A	3/1976	Templeton
4,119,900	A	10/1978	Kremnitz
4,133,404	A	1/1979	Griffin
4,163,977	A	8/1979	Polstorff
4,306,329	A	12/1981	Yokoi
4,369,543	A	1/1983	Chen et al.
4,513,469	A	4/1985	Godfrey et al.
4,545,404	A	10/1985	Redwine
4,545,453	A	10/1985	Yoshimura et al.
4,556,313	A	12/1985	Miller et al.
4,603,753	A	8/1986	Yoshimura et al.
4,626,995	A	12/1986	Lofgren et al.
4,674,048	A	6/1987	Okumura
4,679,152	A	7/1987	Perdue
4,696,074	A	9/1987	Cavalli et al.
4,700,301	A	10/1987	Dyke
4,700,427	A	10/1987	Knepper
4,716,621	A	1/1988	Zoni
4,733,431	A	3/1988	Martin
4,756,049	A	7/1988	Uehara
4,767,237	A	8/1988	Cosman et al.
4,777,416	A	10/1988	George, II et al.
4,777,785	A	10/1988	Rafaels
4,782,550	A	11/1988	Jacobs
4,811,228	A	3/1989	Hyyppa
4,854,000	A	8/1989	Takimoto
4,887,415	A	12/1989	Martin
4,893,025	A	1/1990	Lee
4,909,024	A	3/1990	Jones et al.
4,912,643	A	3/1990	Beirne
4,918,441	A	4/1990	Bohman
4,919,224	A	4/1990	Shyu et al.
4,933,864	A	6/1990	Evans et al.
4,962,453	A	10/1990	Pong et al.
4,974,283	A	12/1990	Holsten et al.
5,002,145	A	3/1991	Waqkaumi et al.
5,017,415	A	5/1991	Cosman et al.
5,086,535	A	2/1992	Grossmeyer et al.
5,093,955	A	3/1992	Blehert et al.
5,109,566	A	5/1992	Kobayashi et al.
5,142,985	A	9/1992	Stearns et al.
5,163,202	A	11/1992	Kawakami et al.
5,163,273	A	11/1992	Wojtkowski et al.
5,165,064	A	11/1992	Mattaboni
5,204,814	A	4/1993	Noonan et al.
5,208,521	A	5/1993	Aoyama
5,216,777	A	6/1993	Moro et al.
5,239,720	A	8/1993	Wood et al.
5,261,139	A	11/1993	Lewis
5,279,672	A	1/1994	Betker, Jr. et al.
5,284,522	A	2/1994	Kobayashi et al.
5,293,955	A	3/1994	Lee
5,303,448	A	4/1994	Hennessey et al.
5,319,828	A	6/1994	Waldhauser et al.
5,321,614	A	6/1994	Ashworth
5,324,948	A	6/1994	Dudar et al.
5,341,540	A	8/1994	Soupert et al.
5,353,224	A	10/1994	Lee et al.
5,369,347	A	11/1994	Yoo
5,410,479	A	4/1995	Coker
5,438,721	A	8/1995	Pahno et al.
5,440,216	A	8/1995	Kim
5,444,965	A	8/1995	Colens
5,446,356	A	8/1995	Kim
5,454,129	A	10/1995	Kell
5,455,982	A	10/1995	Armstrong et al.
5,465,525	A	11/1995	Mifune et al.
5,467,273	A	11/1995	Faibish et al.
5,483,346	A	1/1996	Butzer
5,497,529	A	3/1996	Boesi
5,507,067	A	4/1996	Hoekstra et al.
5,515,572	A	5/1996	Hoekstra et al.
5,528,888	A	6/1996	Miyamoto et al.
5,534,762	A	7/1996	Kim
5,537,017	A	7/1996	Feiten et al.
5,539,953	A	7/1996	Kurz
5,542,146	A	8/1996	Hoekstra et al.
5,548,511	A	8/1996	Bancroft
5,553,349	A	9/1996	Kilstrom et al.
5,555,587	A	9/1996	Guha
5,560,077	A	10/1996	Crotchett
5,568,589	A	10/1996	Hwang
5,611,106	A	3/1997	Wulff
5,611,108	A	3/1997	Knowlton et al.
5,613,261	A	3/1997	Kawakami et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,621,291	A	4/1997	Lee
5,622,236	A	4/1997	Azumi et al.
5,634,237	A	6/1997	Paranjpe
5,634,239	A	6/1997	Tuvin et al.
5,650,702	A	7/1997	Azumi
5,652,489	A	7/1997	Kawakami
5,682,213	A	10/1997	Schmutz
5,682,313	A	10/1997	Edlund et al.
5,682,839	A	11/1997	Grimsley et al.
5,709,007	A	1/1998	Chiang
5,761,762	A	6/1998	Kubo et al.
5,781,960	A	7/1998	Kilstrom et al.
5,787,545	A	8/1998	Colens
5,794,297	A	8/1998	Muta
5,812,267	A	9/1998	Everett, Jr. et al.
5,819,008	A	10/1998	Asama et al.
5,825,981	A	10/1998	Matsuda
5,839,156	A	11/1998	Park et al.
5,841,259	A	11/1998	Kim et al.
5,867,800	A	2/1999	Leif
5,916,111	A	6/1999	Colens
5,926,909	A	7/1999	McGee
5,935,179	A	8/1999	Kleiner et al.
5,940,927	A	8/1999	Haegermarck et al.
5,940,930	A	8/1999	Oh et al.
5,942,869	A	8/1999	Katou et al.
5,943,730	A	8/1999	Boomgaarden
5,943,733	A	8/1999	Tagliaferri
5,959,423	A	9/1999	Nakanishi et al.
5,974,348	A	10/1999	Rocks
6,009,358	A	12/1999	Angott et al.
6,041,471	A	3/2000	Charkey et al.
6,049,745	A	4/2000	Douglas et al.
6,073,427	A	6/2000	Nichols
6,076,025	A	6/2000	Ueno et al.
6,076,227	A	6/2000	Schalig et al.
6,108,076	A	8/2000	Hanseder
6,112,143	A	8/2000	Allen et al.
6,124,694	A	9/2000	Bancroft et al.
6,133,730	A	10/2000	Winn
6,140,146	A	10/2000	Brady et al.
6,140,231	A	10/2000	Lin et al.
6,166,706	A	12/2000	Gallagher et al.
6,226,830	B1	5/2001	Hendriks et al.
6,240,342	B1	5/2001	Fiegert et al.
6,255,793	B1	7/2001	Peless et al.
6,259,979	B1	7/2001	Holmquist
6,285,930	B1	9/2001	Dickson et al.
6,300,737	B1	10/2001	Bergvall et al.
D451,931	S	12/2001	Abramson et al.
6,339,735	B1	1/2002	Peless
6,374,155	B1	4/2002	Wallach et al.
6,385,515	B1	5/2002	Dickson et al.
6,408,226	B1	6/2002	Byrne et al.
6,417,641	B2	7/2002	Peless et al.
6,438,456	B1	8/2002	Feddema et al.
6,442,476	B1	8/2002	Poropat
6,443,509	B1	9/2002	Levin et al.
6,444,003	B1	9/2002	Sutcliffe
6,463,368	B1	10/2002	Feiten et al.
6,465,982	B1	10/2002	Bergvall et al.
6,493,613	B2	12/2002	Peless et al.
6,496,754	B2	12/2002	Song et al.
6,496,755	B2	12/2002	Wallach et al.
6,507,773	B2	1/2003	Parker et al.
6,525,509	B1	2/2003	Petersson et al.
6,532,404	B2	3/2003	Colens
6,535,793	B2	3/2003	Allard
6,548,982	B1	4/2003	Papanikolopoulos et al.
6,571,415	B2	6/2003	Gerber et al.
6,574,536	B1	6/2003	Kawagoe et al.
6,580,246	B2	6/2003	Jacobs
6,580,978	B1	6/2003	McTamaney
6,584,376	B1	6/2003	Kommer
6,586,908	B2	7/2003	Petersson et al.
6,594,844	B2	7/2003	Jones
6,604,022	B2	8/2003	Parker
6,605,156	B1	8/2003	Clark et al.
6,611,120	B2	8/2003	Song et al.
6,611,734	B2	8/2003	Parker et al.
6,611,738	B2	8/2003	Ruffner
6,615,108	B1	9/2003	Peless et al.
6,658,693	B1	12/2003	Reed, Jr.
6,661,239	B1	12/2003	Ozick
6,671,592	B1	12/2003	Bisset et al.
6,690,134	B1	2/2004	Jones et al.
6,741,054	B2	5/2004	Koselka et al.
6,748,297	B2	6/2004	Song et al.
6,764,373	B1	7/2004	Osawa et al.
6,781,338	B2	8/2004	Jones et al.
6,809,490	B2	10/2004	Jones et al.
6,830,120	B1	12/2004	Yashima et al.
6,841,963	B2	1/2005	Song et al.
6,845,297	B2	1/2005	Allard
6,850,024	B2	2/2005	Peless et al.
6,870,792	B2	3/2005	Chiappetta
6,883,201	B2	4/2005	Jones et al.
6,885,912	B2	4/2005	Peless et al.
6,901,624	B2	6/2005	Mori et al.
D510,066	S	9/2005	Hickey et al.
6,938,298	B2	9/2005	Aasen
6,940,291	B1	9/2005	Ozick
6,956,348	B2	10/2005	Landry et al.
6,971,140	B2	12/2005	Kim
6,984,952	B2	1/2006	Peless et al.
6,999,850	B2	2/2006	McDonald
7,024,278	B2	4/2006	Chiappetta et al.
7,069,124	B1	6/2006	Whittaker et al.
7,085,624	B2	8/2006	Aldred et al.
7,103,457	B2	9/2006	Dean
7,155,309	B2	12/2006	Peless et al.
7,203,576	B1	4/2007	Wilson et al.
7,206,677	B2	4/2007	Hulden
7,239,944	B2	7/2007	Dean
D559,867	S	1/2008	Abramson
7,349,759	B2	3/2008	Peless et al.
D573,610	S	7/2008	Abramson
7,441,392	B2	10/2008	Lilliestielke et al.
7,481,036	B2	1/2009	Lilliestielke et al.
7,525,287	B2	4/2009	Miyashita et al.
7,729,801	B2	6/2010	Abramson
8,046,103	B2	10/2011	Abramson et al.
D652,431	S	1/2012	Naslund
D656,163	S	3/2012	Johansson et al.
8,136,333	B1	3/2012	Levin et al.
8,306,659	B2	11/2012	Abramson et al.
8,413,616	B2	4/2013	Bergquist
8,532,822	B2	9/2013	Abramson et al.
8,634,960	B2	1/2014	Sandin et al.
8,781,627	B2	7/2014	Sandin et al.
8,868,237	B2	10/2014	Sandin et al.
8,954,193	B2	2/2015	Sandin et al.
2001/0022506	A1	9/2001	Peless et al.
2001/0047231	A1	11/2001	Peless et al.
2002/0011813	A1	1/2002	Koselka et al.
2002/0016649	A1	2/2002	Jones
2002/0120364	A1	8/2002	Colens
2002/0140393	A1	10/2002	Peless et al.
2002/0156556	A1	10/2002	Ruffner
2002/0160845	A1	10/2002	Simonsen
2002/0173877	A1	11/2002	Zweig
2003/0018423	A1	1/2003	Saller et al.
2003/0019071	A1	1/2003	Field et al.
2003/0023356	A1	1/2003	Keable
2003/0025472	A1	2/2003	Jones et al.
2003/0055337	A1	3/2003	Lin
2003/0060928	A1	3/2003	Abramson et al.
2003/0120389	A1	6/2003	Abramson et al.
2003/0137268	A1	7/2003	Papanikolopoulos et al.
2003/0144774	A1	7/2003	Trissel et al.
2003/0182914	A1	10/2003	Shibata et al.
2003/0192144	A1	10/2003	Song et al.
2003/0208304	A1	11/2003	Peless et al.
2003/0216834	A1	11/2003	Allard

(56) **References Cited**

U.S. PATENT DOCUMENTS

2003/0233177	A1	12/2003	Johnson et al.
2003/0234325	A1	12/2003	Marino et al.
2004/0010343	A1	1/2004	Dean
2004/0020000	A1	2/2004	Jones
2004/0030448	A1	2/2004	Solomon
2004/0030449	A1	2/2004	Solomon
2004/0030450	A1	2/2004	Solomon
2004/0030571	A1	2/2004	Solomon
2004/0031113	A1	2/2004	Wosewick et al.
2004/0036618	A1	2/2004	Ku et al.
2004/0049877	A1	3/2004	Jones et al.
2004/0068351	A1	4/2004	Solomon
2004/0068415	A1	4/2004	Solomon
2004/0068416	A1	4/2004	Solomon
2004/0076324	A1	4/2004	Burl et al.
2004/0088079	A1	5/2004	Lavarec et al.
2004/0111184	A1	6/2004	Chiappetta et al.
2004/0111196	A1	6/2004	Dean
2004/0134336	A1	7/2004	Solomon
2004/0134337	A1	7/2004	Solomon
2004/0156541	A1	8/2004	Jeon et al.
2004/0158357	A1	8/2004	Lee et al.
2004/0187457	A1	9/2004	Colens
2004/0193348	A1	9/2004	Gray
2004/0200505	A1	10/2004	Taylor et al.
2004/0204792	A1	10/2004	Taylor et al.
2004/0211444	A1	10/2004	Taylor et al.
2004/0220000	A1	11/2004	Falone et al.
2004/0236468	A1	11/2004	Taylor et al.
2004/0244138	A1	12/2004	Taylor et al.
2005/0000543	A1	1/2005	Taylor et al.
2005/0007057	A1	1/2005	Peless et al.
2005/0010331	A1	1/2005	Taylor et al.
2005/0020374	A1	1/2005	Wang
2005/0038578	A1	2/2005	McMurtry
2005/0097952	A1	5/2005	Steph et al.
2005/0108999	A1	5/2005	Bucher
2005/0113990	A1	5/2005	Peless et al.
2005/0156562	A1	7/2005	Cohen et al.
2005/0197766	A1	9/2005	Fiann
2005/0204717	A1	9/2005	Colens
2005/0251292	A1	11/2005	Casey et al.
2005/0278094	A1	12/2005	Swinbanks et al.
2005/0287038	A1	12/2005	Dubrovsky et al.
2006/0090438	A1	5/2006	Hunt
2006/0293794	A1	12/2006	Harwig et al.
2007/0016328	A1	1/2007	Ziegler et al.
2007/0142964	A1	6/2007	Abramson
2007/0150109	A1	6/2007	Peless et al.
2008/0039974	A1	2/2008	Sandin et al.
2008/0039991	A1	2/2008	May
2008/0049217	A1	2/2008	Cappelletti
2008/0097645	A1	4/2008	Abramson et al.
2008/0109126	A1	5/2008	Sandin
2008/0167753	A1	7/2008	Peless et al.
2008/0183349	A1	7/2008	Abramson et al.
2009/0254218	A1	10/2009	Sandin et al.
2010/0059000	A1	3/2010	Bergquist
2011/0130875	A1	6/2011	Abramson
2012/0041594	A1	2/2012	Abramson et al.
2012/0226381	A1	9/2012	Abramson et al.
2013/0274920	A1	10/2013	Abramson et al.
2014/0102061	A1	4/2014	Sandin et al.
2014/0102062	A1	4/2014	Sandin et al.
2015/0006015	A1	1/2015	Sandin et al.

FOREIGN PATENT DOCUMENTS

EP	0792726	9/1997
EP	1331537 A1	7/2003
EP	1704766	9/2006
FR	2789643	8/2000
FR	2828589	8/2001
GB	2142447	1/1985
GB	2283838	5/1995
GB	2382157	5/2003
JP	62-120510	6/1987
JP	62-154008	7/1987
JP	62154008	7/1987
JP	63-183032	7/1988
JP	63-241610	10/1988
JP	2-6312	1/1990
JP	03-051023	3/1991
JP	H 04320612	11/1992
JP	06-327598	11/1994
JP	07-129239	5/1995
JP	7-295636	11/1995
JP	8-16776	1/1996
JP	08-089451	4/1996
JP	08-152916	6/1996
JP	9-179625	7/1997
JP	9185410	7/1997
JP	11-508810	8/1999
JP	11-510935	9/1999
JP	2001-258807	9/2001
JP	2001-275908	10/2001
JP	2001-525567	12/2001
JP	2002-78650	3/2002
JP	2002-204768	7/2002
JP	2002-532178	10/2002
JP	8170	10/2002
JP	2002-323925	11/2002
JP	3375843	11/2002
JP	2002-355206	12/2002
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JP	2002-360482	12/2002
JP	2003-10076	1/2003
JP	2003-5296	2/2003
JP	2003-036116	2/2003
JP	2003-38401	2/2003
JP	2003-38402	2/2003
JP	2003-505127	2/2003
JP	2003036116	2/2003
JP	2003-061882	3/2003
JP	2003-310489	11/2003
WO	WO 95/26512	10/1995
WO	WO 97/40734	11/1997
WO	WO97/41451	11/1997
WO	WO98/53456	11/1998
WO	WO99/16078	4/1999
WO	WO99/28800	6/1999
WO	WO99/38056	7/1999
WO	WO99/38237	7/1999
WO	WO99/59042	11/1999
WO	WO00/04430	1/2000
WO	WO00/36962	6/2000
WO	WO00/38026	6/2000
WO	WO00/38029	6/2000
WO	WO00/78410	12/2000
WO	WO01/06904	2/2001
WO	WO01/06905	2/2001
WO	WO02/39864	5/2002
WO	WO02/39868	5/2002
WO	WO02/058527	8/2002
WO	WO 2/062194	8/2002
WO	WO02/067744	9/2002
WO	WO02/067745	9/2002
WO	WO02/074150	9/2002
WO	WO02/075356	9/2002
WO	WO02/075469	9/2002
WO	WO02/075470	9/2002
WO	WO02/101477	12/2002
WO	WO 3/026474	4/2003
WO	WO03/040845	5/2003
WO	WO03/040846	5/2003
WO	WO03065140	8/2003
WO	03/083594	10/2003
WO	WO2004/006034	1/2004
WO	WO2004004533 A1	1/2004
WO	WO2004058028 A2	1/2004
WO	WO2005/055795	6/2005

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

WO	WO2005077244	A1	8/2005
WO	WO2006068403	A1	6/2006

OTHER PUBLICATIONS

Kimura et al., "Stuck Evasion Control for Active Wheel Passive-Joint Snake-like Mobile Robot 'Genbu'." Proceedings of the 2004 IEEE International Conference on Robotics 8 Automation New Orleans, LA Apr. 2004, 6 pages.

Kozlowski and Pazderski, "Modeling and Control of a 4-wheel Skid-steering Mobile Robot," *International J. of Applied Mathematics and Computer Science*, 2004, 14:477-496.

Angle et al., U.S. Appl. No. 60/177,703, 16 pages, published Feb. 7, 2002, available at http://portal.uspto.gov/external/portal/pair, accessed Jul. 11, 2012.

Bohn et al., "Super-distributed RFID Tag Infrastructures", Lecture Notes in Computer Science, Springer Verlag, Berlin, DE, vol. 3295, Nov. 11, 2004, pp. 1-12.

Campbell et al., U.S. Appl. No. 60/741,442, 113 pages, published Jun. 7, 2007, available at http://patentscope.wipo.int/search/docservicepdf_pct/id00000005206306.pdf, accessed Jul. 11, 2012.

Casey et al., U.S. Appl. No. 60/582,992, 24 pages, published Nov. 10, 2005, available at http://portal.uspto.gov/external/portal/pair accessed Jul. 11, 2012.

Domnitcheva "Smart Vacuum Cleaner an Autonomous Location-Aware Cleaning Device" Proceedings of the International Conference on Ubiquitous Computing, Sep. 2004, pp. 1-2.

Doty et al., "Sweep Strategies for a Sensory-Driven, Behavior-Based Vacuum Cleaning Agent," AAAI 1993 Fall Symposium Series, Instantiating Real-World Agents, Oct. 22-24, 1993, pp. 1-6.

Electrolux, "Designed for the well-lived home," Retrieved from the Internet: URL<http://www.electroluxusa.com/node57.as[?currentURL=node142.asp%3F >. Accessed Mar. 2005, 2 pages.

eVac Robotic Vacuum S1727 Instruction Manual, Sharper Image Corp, Copyright 2004, 16 pages.

Everyday Robots, "Everyday Robots: Reviews, Discussion and News for Consumers," Aug. 2004, Retrieved from the Internet: URL< www.everydayrobots.com/index.php?option=content &task=view&id=9> (Sep. 2012), 4 pages.

Facts on Trilobite, webpage, Retrieved from the Internet: URL< http://trilobiteelectroluxse/presskit_en/model11335asp?print =yes &pressID=>, accessed Dec. 2003, 2 pages.

TheRobotStore.com, "Friendly Robotics Robotic Vacuum RV400—The Robot Store," www.therobotstore.com/s.nl/sc.9/category.-109/it.A/id.43/f, Apr. 2005, 1 page.

Gat, "Robust Low-Computation Sensor-driven Control for Task-Directed Navigation," Proc of IEEE International Conference on Robotics and Automation , Sacramento, CA, Apr. 1991, pp. 2484-2489.

Hicks et al., "Survey of Robot Lawn Mowers," http://www.robotics.uc.edu/papers/paper2000/lawnmower.pdf, 2000, 8 pages.

Hitachi: News release: "The home cleaning robot of the autonomous movement type (experimental machine)," Retrieved from the Internet: URL< www.i4u.com./japanreleases/hitachirobot.htm>, Mar. 2005, 5 pages.

Wired News: Kahney, "Robot Vacs are in the House," Retrieved from the Internet: URLwww.wired.com/news/technology/o,1282,59237,00.html, Jun. 2003, 6 pages.

Karcher, "Product Manual Download Karch", available at www.karcher.com, 2004, 16 pages.

Karcher RC 3000 Cleaning Robot-user manual Manufacturer: Alfred-Karcher GmbH & Co, Cleaning Systems, Alfred Karcher-Str 28-40, PO Box 160, D-71349 Winnenden, Germany, Dec. 2002, 8 pages.

Karcher "Karcher RoboCleaner RC 3000," Retrieved from the Internet: URL<www.robocleaner.de/english/screen3.html>. 4 pages, Dec. 2003.

Karcher USA, RC3000 Robotic Cleaner, website: http://www.karcher-usa.com/showproducts.php?op=view prod&paraml=143 &param2=&param3=, 3 pages, accessed Mar. 2005.

Koolvac Robotic Vacuum Cleaner Owner's Manual, Koolatron, 2004, 13 pages.

Kubitz et al., "Application of radio frequency identification devices to support navigation of autonomous mobile robots," Vehicular Technology Conference, vol. 1, May 1997, pp. 126-130.

Matthies et al., "Detecting Water Hazards for Autonomous Off-Road Navigation," Proceedings of SPIE Conference 5083: Unmanned Ground Vehicle Technology V, Orlando, F:, Apr. 2003, pp. 231-242.

Morland,"Autonomous Lawnmower Control", Downloaded from the Internet at: http://cns.bu.edu/~cjmorlan/robotics/lawnmower/report.pdf, Jul. 2002, 10 pages.

NorthStar Low-Cost, Indoor Localization, Evolution robotics, Powering Intelligent Products.

Put Your Roomba . . . On, Automatic webpages: http://www.acomputeredge.com/roomba, accessed Apr. 2005, 5 pages.

RoboMaid Sweeps Your Floors So You Won't Have to, the Official Site, website: Retrieved from the Internet: URLhttp://therobomaid.com. accessed Mar. 2005, 2 pages.

On Robo, "Robot Reviews Samsung Robot Vacuum (VC-RP30W)," Retrieved from the Internet: URL <www.onrobo.com/reviews/AT_Home/vacuum_cleaners/on00vcrb30rosam/index.htm>. 2005, 2 pages.

Robotic Vacuum Cleaner-Blue, website: http://www.sharperimage.com/us/en/catalog/productview.jhtml?sku=S1727BLU, accessed Mar. 18, 2005, 2 pages.

Schofield, "Neither Master nor slave-A Practical Study in the Development and Employment of Cleaning Robots, Emerging Technologies and Factory Automation," 1999 Proceedings ETFA'99 1999 7th IEEE International Conference on Barcelona, Spain, Oct. 1999, pp. 1427-1434.

Thrun, "Learning Occupancy Grid Maps With Forward Sensor Models," Autonomous Robots 15, Sep. 2003, 28 pages.

Wigley, "The Electric Lawn", in *The American Lawn*, Princeton Architectural Press New York with Canadian Centre for Architecture Montreal, 1999, pp. 155-195.

Zoombot Remote Controlled Vaccuum-RV-500 NEW Roomba 2, website: http://cgi.ebay.com/ws/eBayISAPI.d11?ViewItem&category=43526&item=4373497618&rd=1, accessed Apr. 2005, 7 pages.

United States Office Action issued in U.S. Appl. No. 11/688,22, dated Feb. 24, 2011.

United States Office Action issued in U.S. Appl. No. 12/488,094, dated Jan. 26, 2011.

United States Office Action issued in U.S. Appl. No. 11/688,213, dated Jan. 27, 2011.

United States Office Action issued in U.S. Appl. No. 12/488,094, dated Jul. 28, 2011.

United States Office Action issued in U.S. Appl. No. 11/688,225, dated Nov. 10, 2011.

United States Office Action issued in U.S. Appl. No. 11/688,225 dated Feb. 24, 2011.

Communication from a foreign patent office in counterpart application PCT/US2007/064326, dated Jul. 17, 2008.

International Preliminary Report on Patentability issued in International Application No. PCT/US2007/064323, dated Sep. 23, 2008.

International Preliminary Report on Patentability issued in International Application No. PCT/US2007/064326, dated Sep. 23, 2008.

Partial International Search Report issued in International Application No. PCT/US2007/064323 dated Mar. 14, 2008.

United States Office Action issued in U.S. Appl. No. 11/688,213, dated Nov. 2, 2011, 12 pages.

United States Office Action issued in U.S. Appl. No. 11/688,213, dated Aug. 16, 2012, 14 pages.

United States Office Action issued in U.S. Appl. No. 11/688,213, dated May 22, 2013, 12 pages.

United States Office Action issued in U.S. Appl. No. 11/688,213, dated Oct. 3, 2013, 12 pages.

United States Notice of Allowance issued in U.S. Appl. No. 11/688,213, dated Jun. 18, 2014, 5 pages.

(56) **References Cited**

OTHER PUBLICATIONS

United States Notice of Allowance issued in U.S. Appl. No. 12/488,094, dated Apr. 12, 2012, 11 pages.
United States Notice of Allowance issued in U.S. Appl. No. 12/488,094, dated Aug. 24, 2012, 13 pages.
United States Notice of Allowance issued in U.S. Appl. No. 12/488,094, dated Feb. 14, 2013, 10 pages.
United States Notice of Allowance issued in U.S. Appl. No. 12/488,094, dated Jun. 19, 2013, 11 pages.
United States Notice of Allowance issued in U.S. Appl. No. 12/488,094, dated Jan. 31, 2014, 6 pages.
United States Notice of Allowance issued in U.S. Appl. No. 12/488,094, dated May 9, 2014, 6 pages.
Extended European Search Report issued in European Application No. 15202591.2 on Aug. 18, 2016, 7 pages.

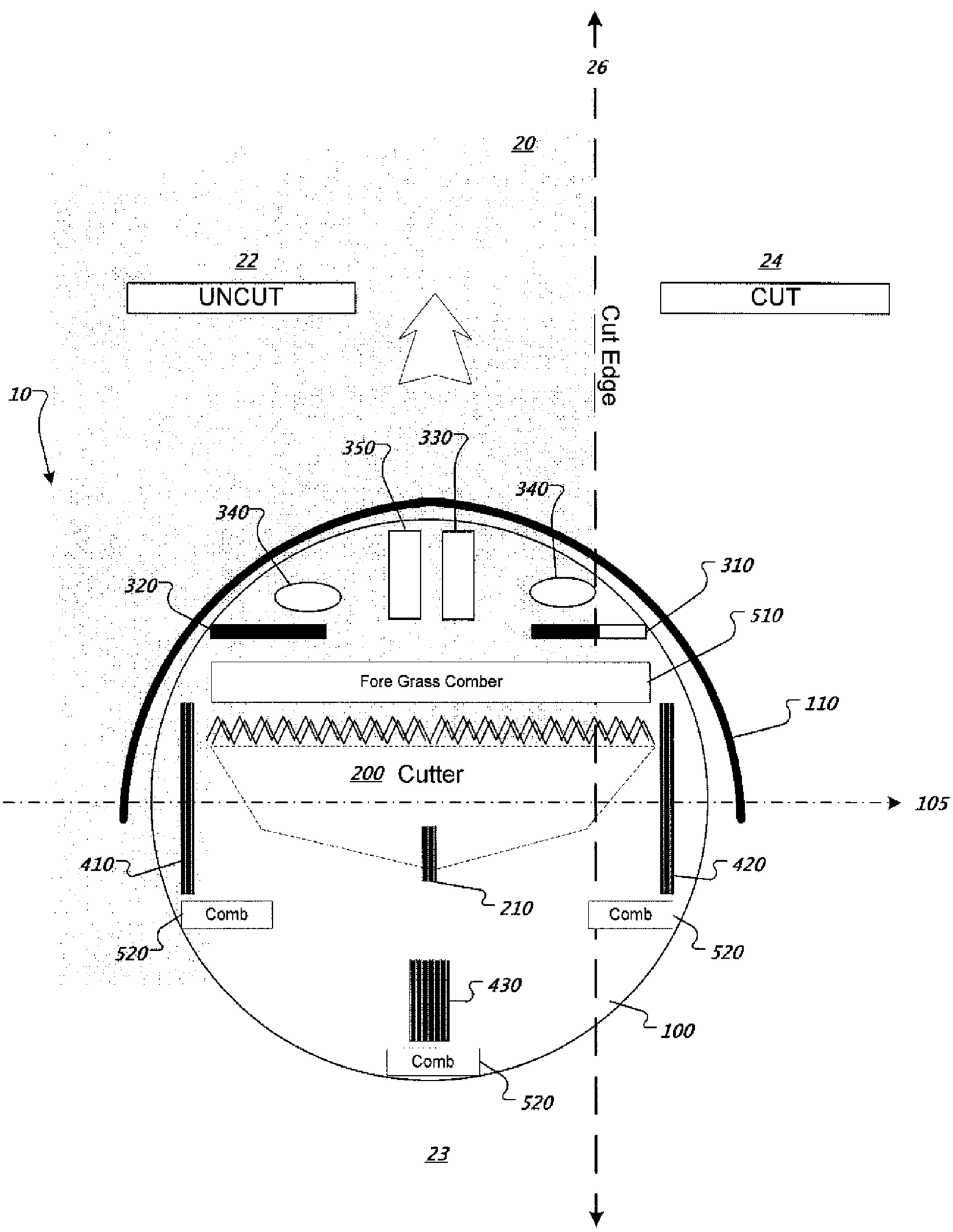

26
20
22
UNCUT
24
CUT
Cut Edge
10
350
330
340
340
320
310
510
Fore Grass Comber
110
200 Cutter
105
410
420
210
Comb
Comb
520
520
430
Comb
520
100
23

FIG. 1A

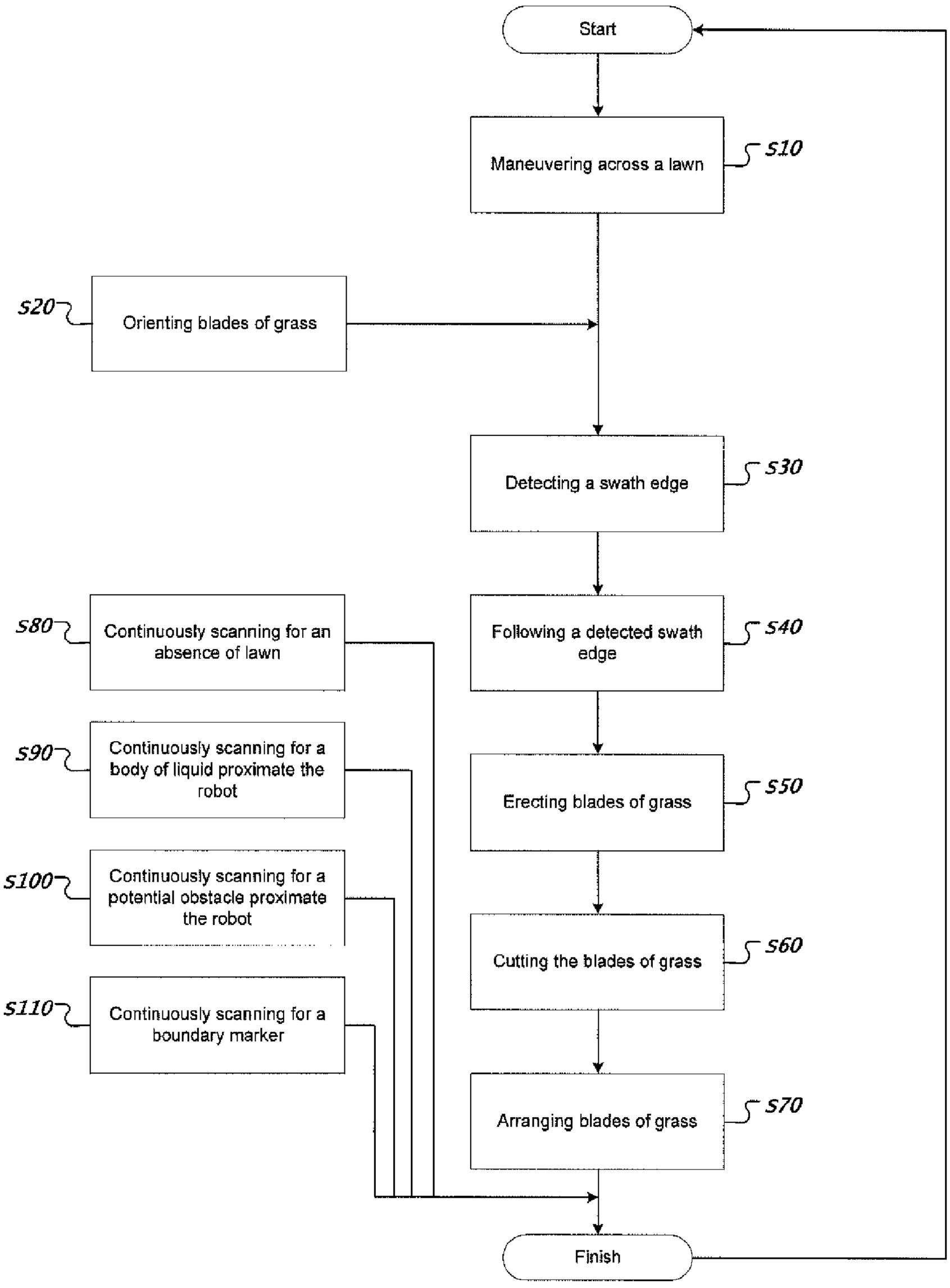

Start
Maneuvering across a lawn
S10
S20
Orienting blades of grass
Detecting a swath edge
S30
S80
Continuously scanning for an absence of lawn
Following a detected swath edge
S40
S90
Continuously scanning for a body of liquid proximate the robot
Erecting blades of grass
S50
S100
Continuously scanning for a potential obstacle proximate the robot
Cutting the blades of grass
S60
S110
Continuously scanning for a boundary marker
Arranging blades of grass
S70
Finish

FIG. 1B

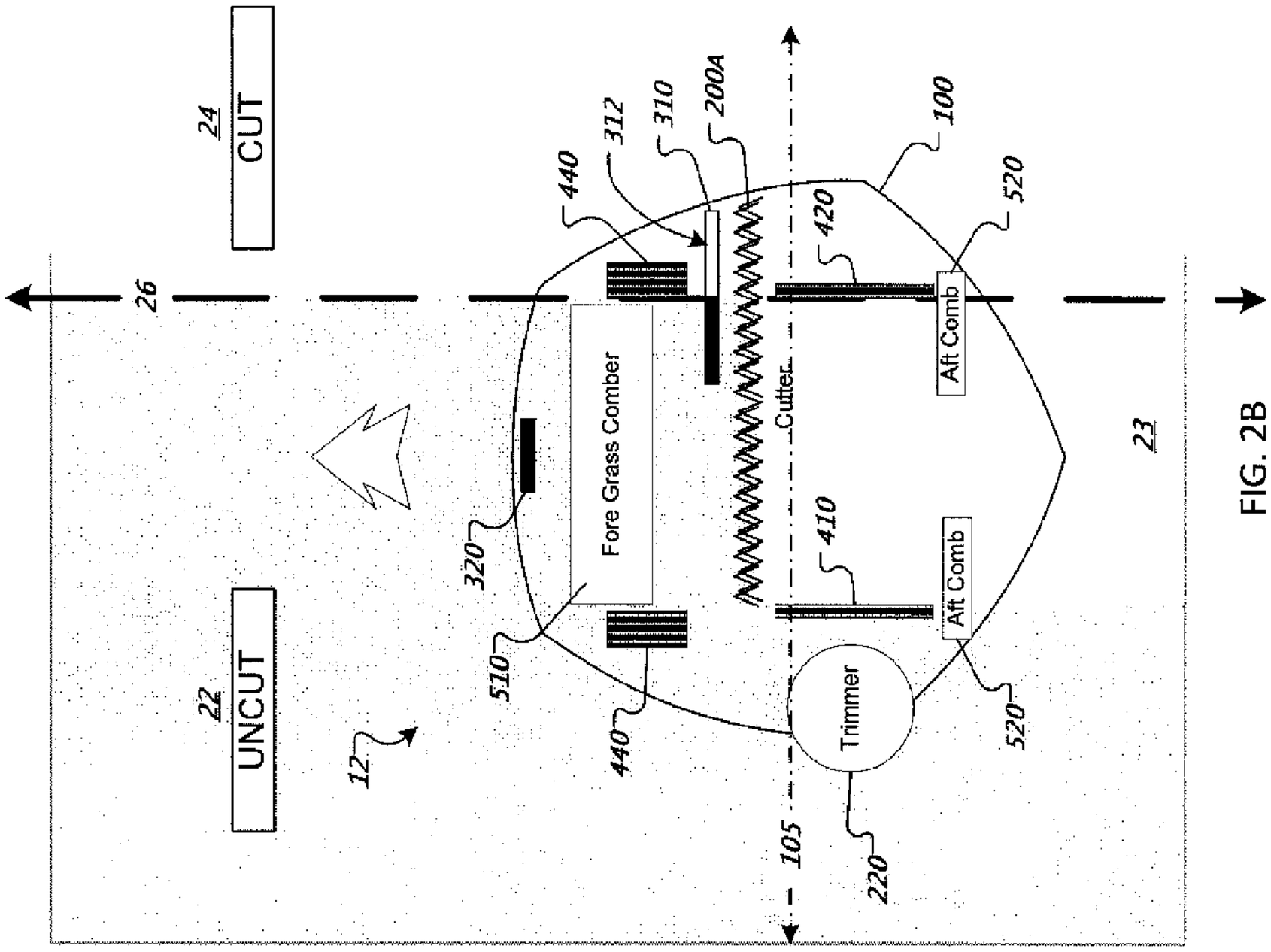

24
CUT
26
22
UNCUT
12
440
312
310
200A
100
420
520
Fore Grass Comber
Cutter
Aft Comb
320
510
410
Trimmer
105
220
23

FIG. 2B

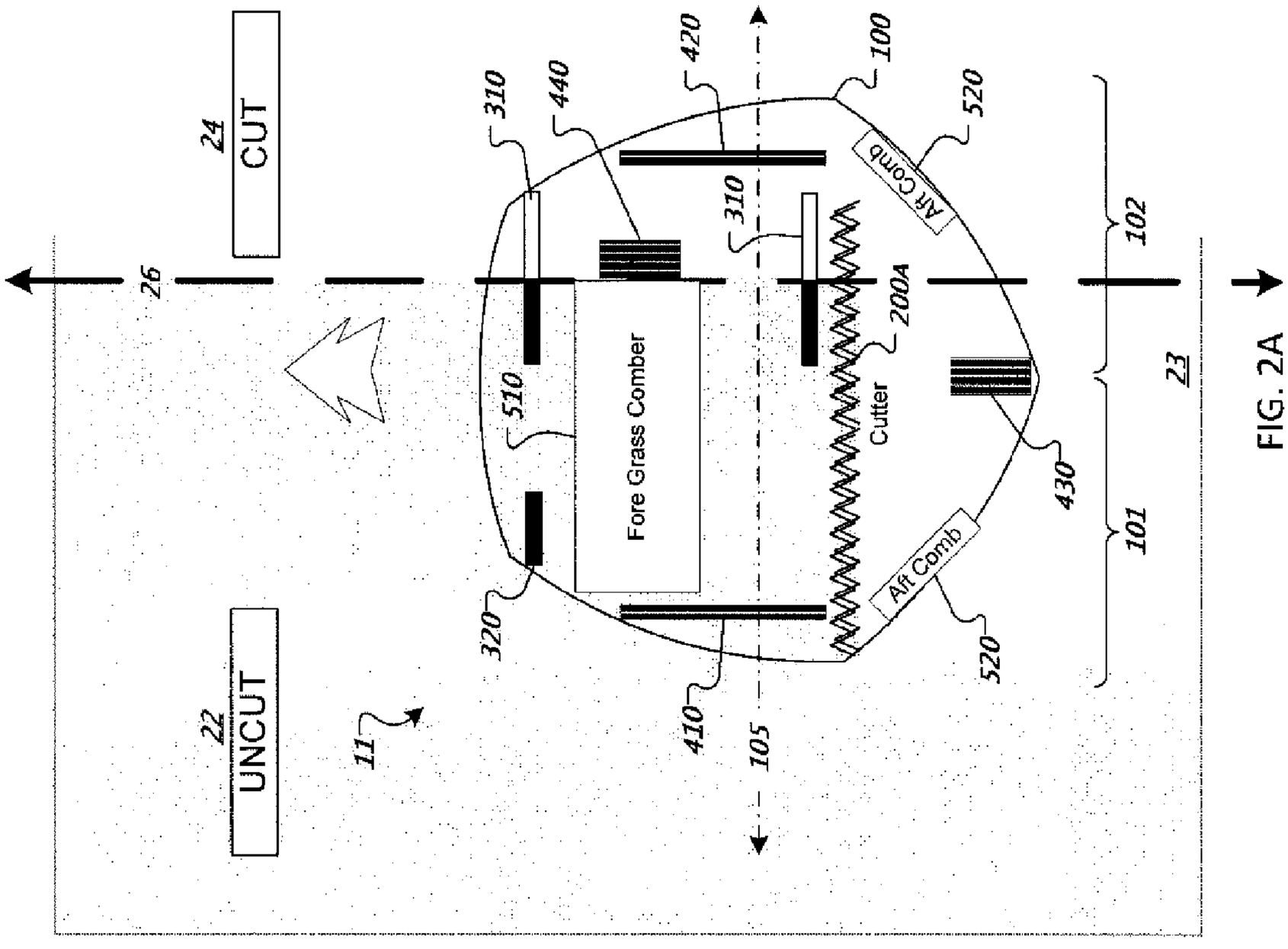

24
CUT
26
22
UNCUT
11
310
440
420
100
520
Aft Comb
310
102
Fore Grass Comber
510
200A
Cutter
430
320
101
Aft Comb
520
410
105
23

FIG. 2A

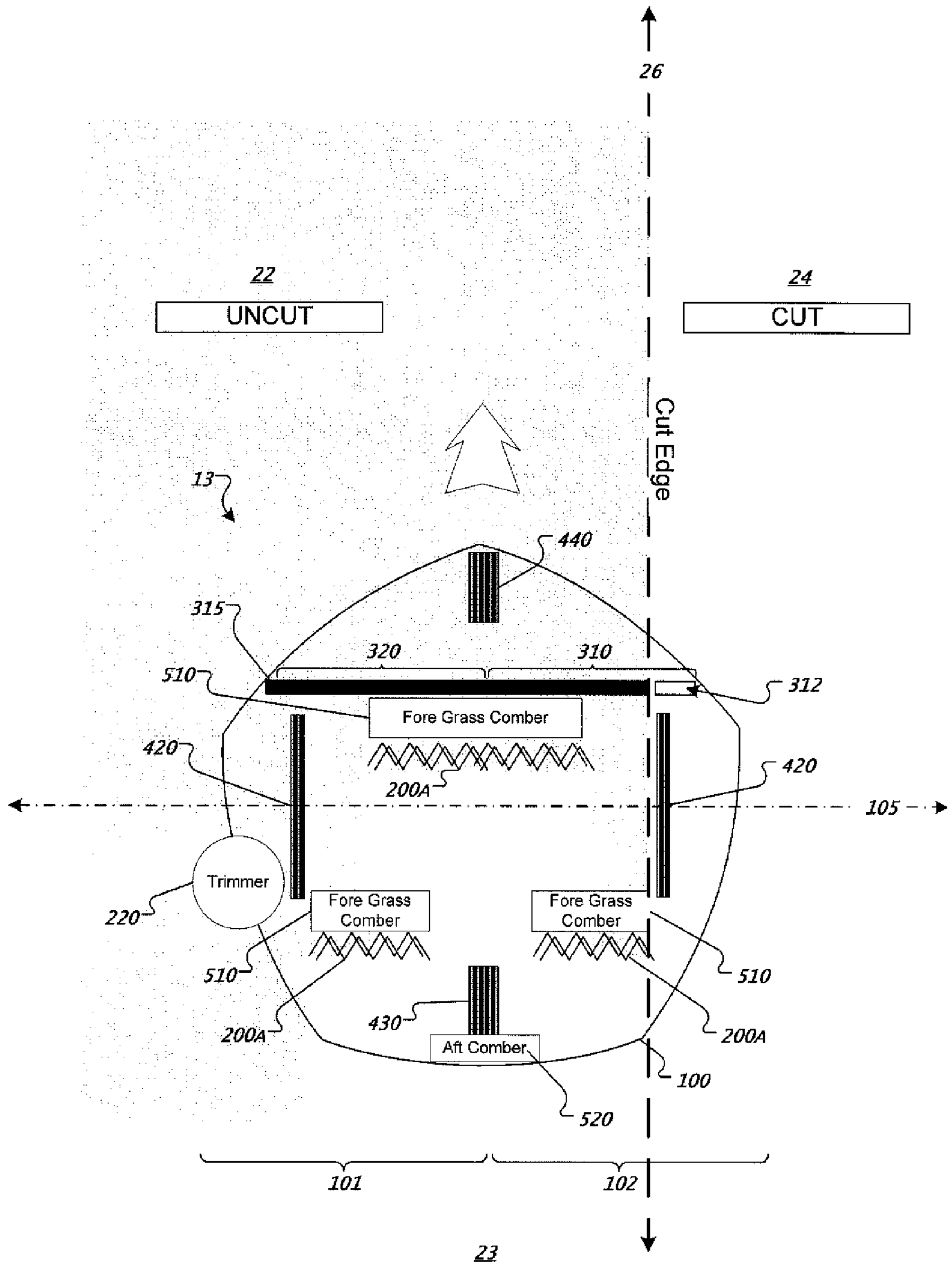

26
22
24
UNCUT
CUT
Cut Edge
13
440
315
320
310
510
312
Fore Grass Comber
420
200A
420
105
Trimmer
220
Fore Grass Comber
Fore Grass Comber
510
510
430
200A
200A
Aft Comber
100
520
101
102
23

FIG. 2C

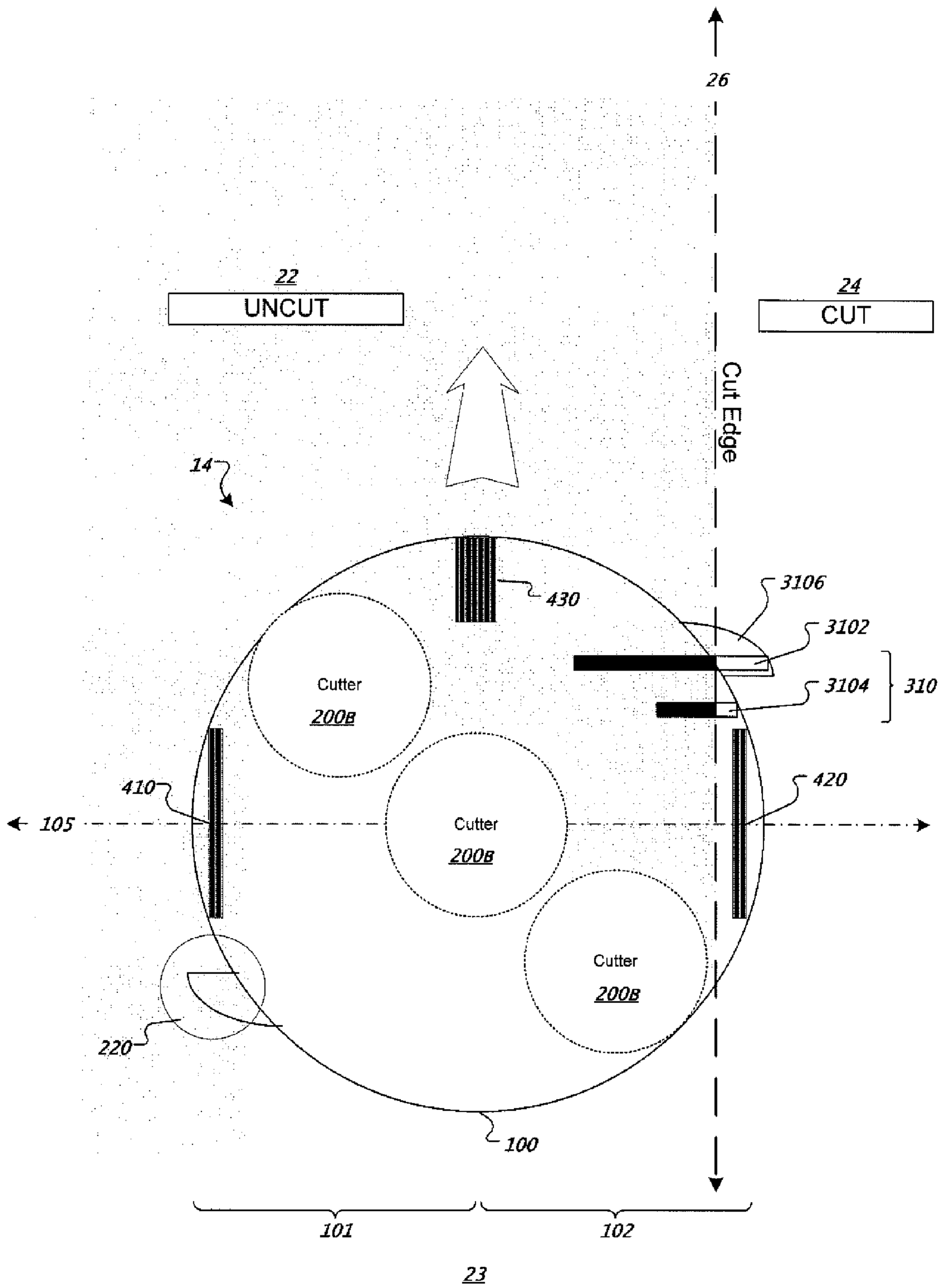

26
22
UNCUT
24
CUT
Cut Edge
14
430
3106
3102
3104
310
Cutter
200B
410
420
105
Cutter
200B
Cutter
200B
220
100
101
102
23

FIG. 3A

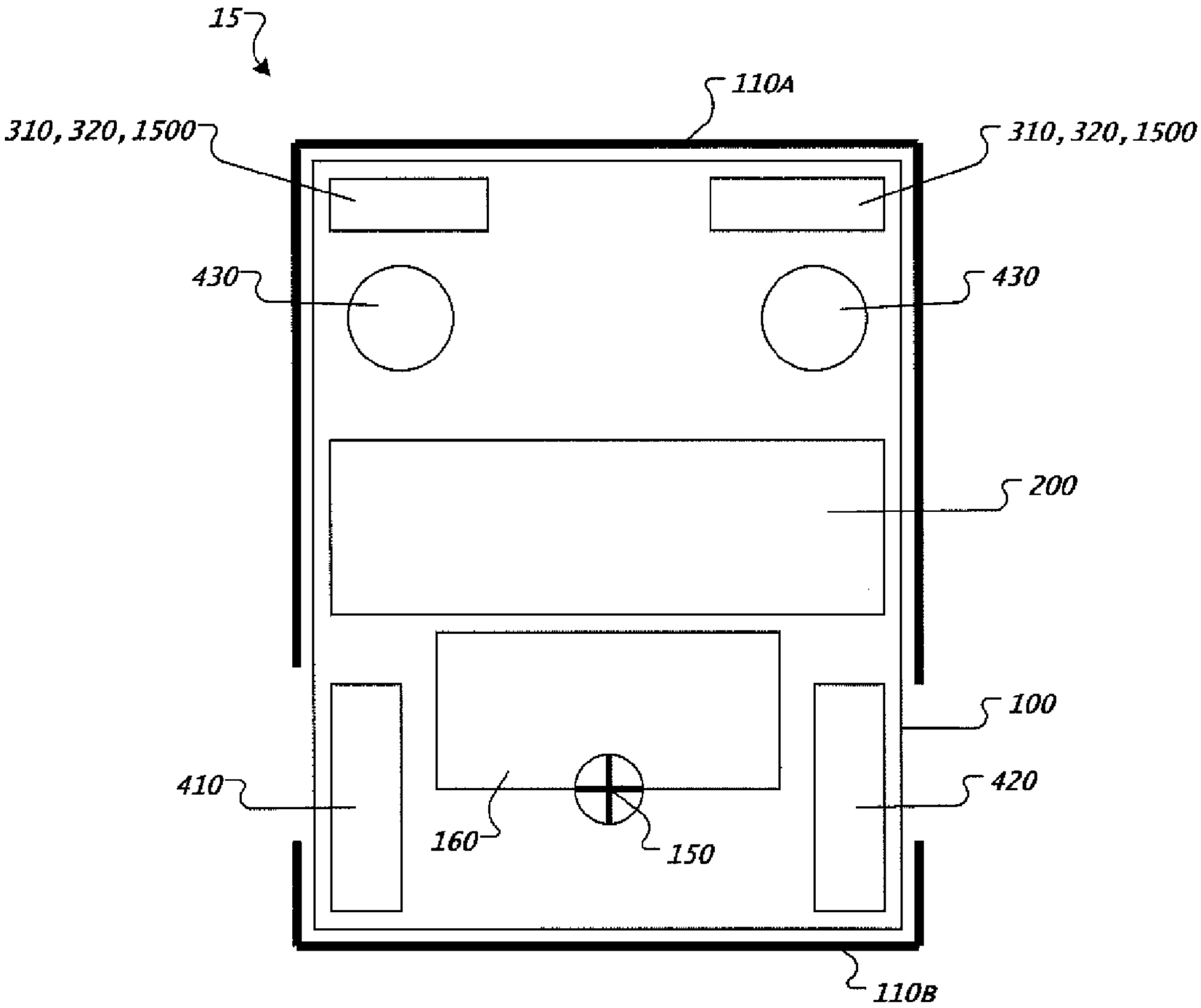

15
110A
310, 320, 1500
310, 320, 1500
430
430
200
100
410
420
160
150
110B

FIG. 3B

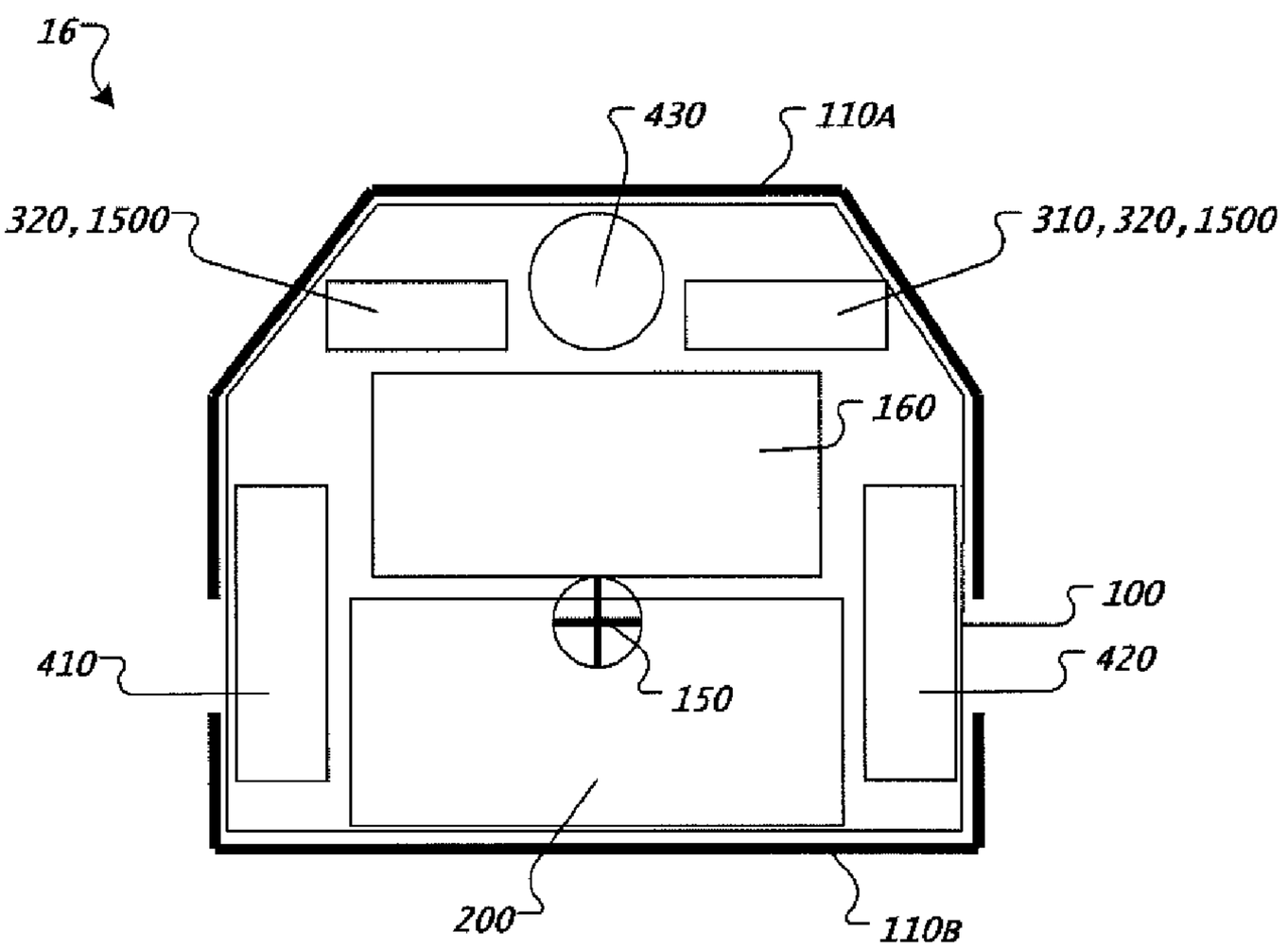

16
430
110A
310, 320, 1500
310, 320, 1500
160
100
410
420
150
200
110B

FIG. 3C

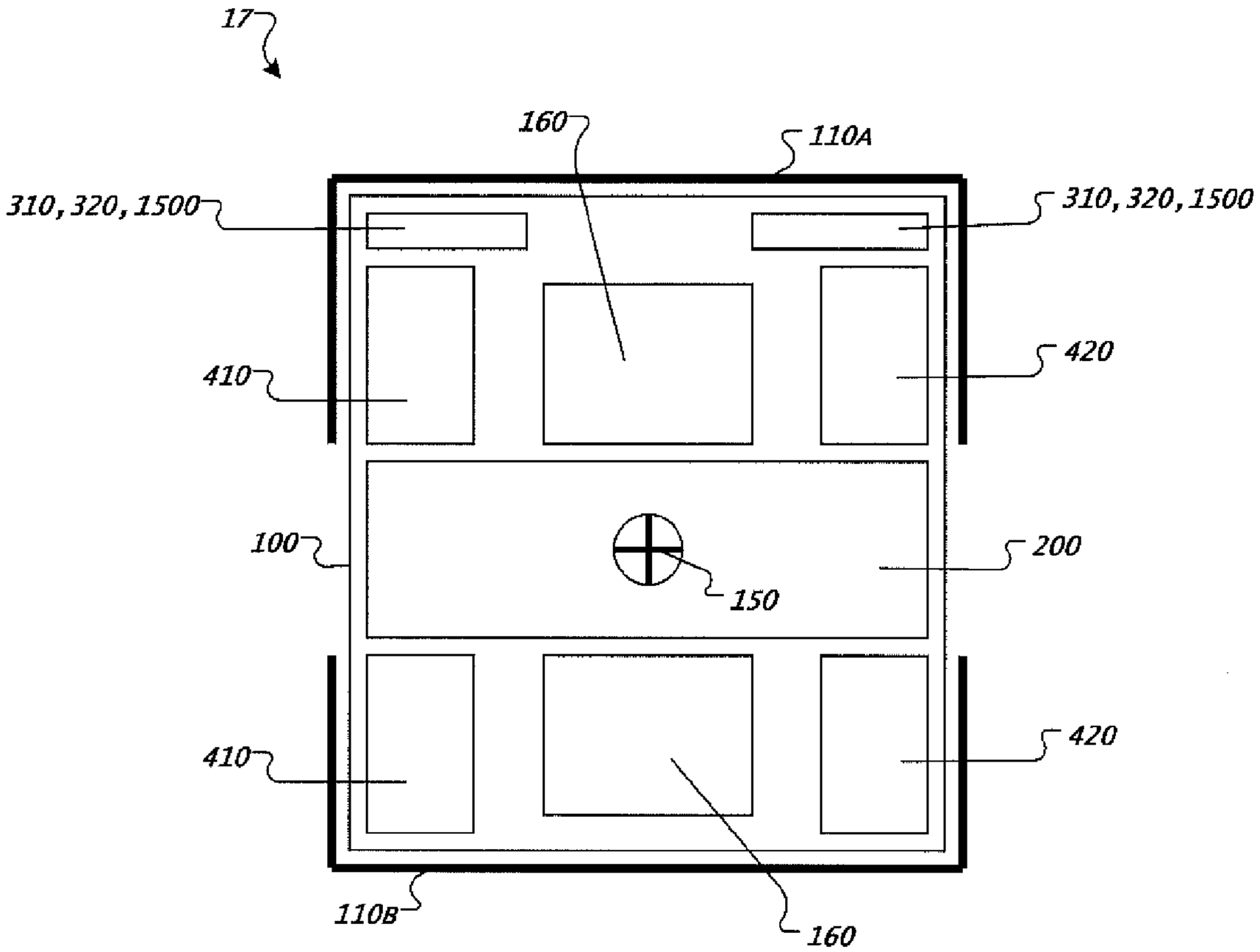

17
160
110A
310, 320, 1500
310, 320, 1500
410
420
100
200
150
410
420
110B
160

FIG. 3D

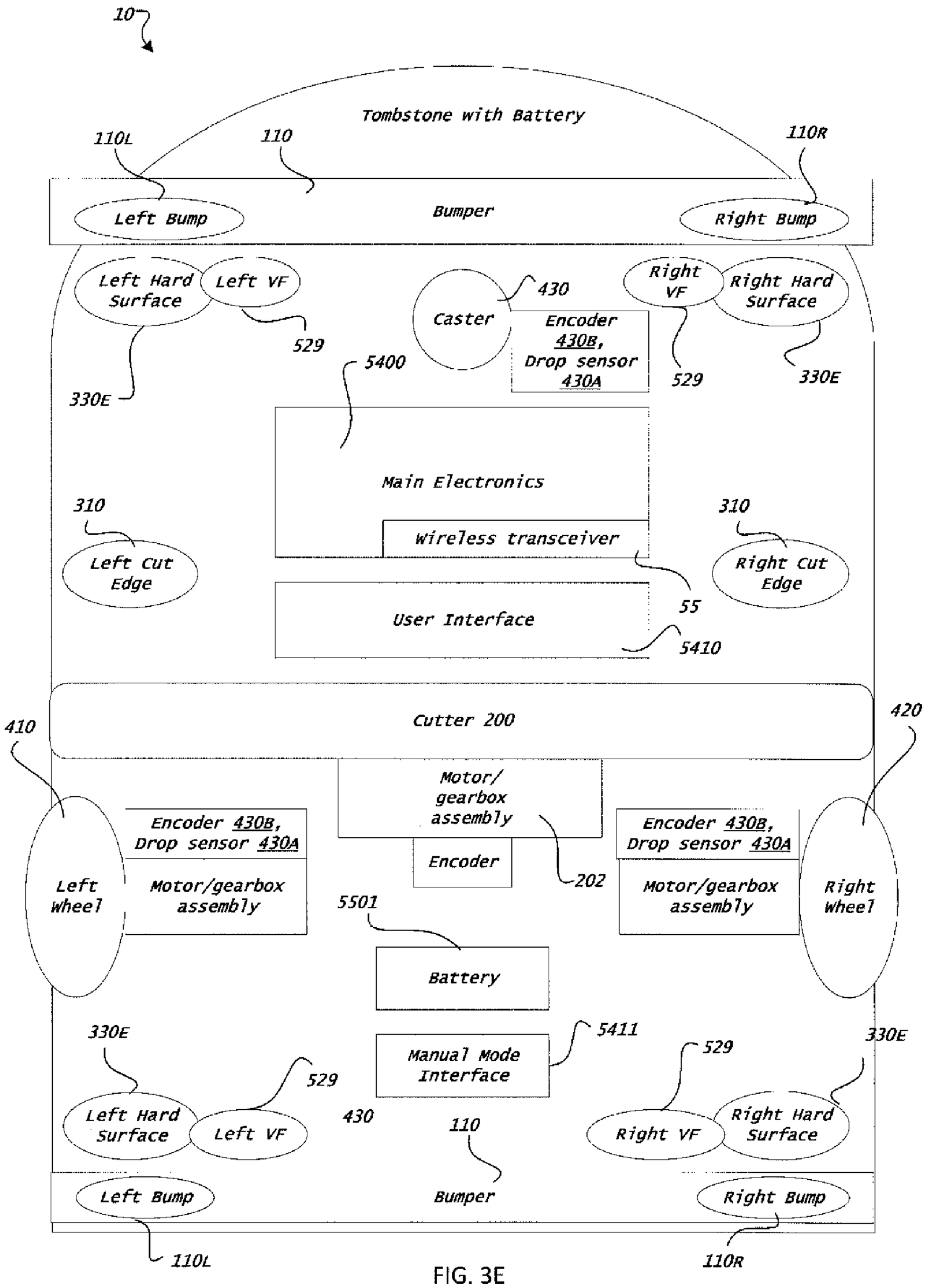

10
Tombstone with Battery
110L
110
110R
Left Bump
Bumper
Right Bump
Left Hard Surface
Left VF
529
330E
Caster
430
Encoder 430B, Drop sensor 430A
Right VF
Right Hard Surface
529
330E
5400
Main Electronics
Wireless transceiver
55
310
Left Cut Edge
310
Right Cut Edge
User Interface
5410
Cutter 200
410
420
Motor/ gearbox assembly
Encoder
202
Encoder 430B, Drop sensor 430A
Motor/gearbox assembly
Left Wheel
Encoder 430B, Drop sensor 430A
Motor/gearbox assembly
Right Wheel
5501
Battery
330E
Manual Mode Interface
5411
529
330E
529
Left Hard Surface
Left VF
430
110
Right VF
Right Hard Surface
Left Bump
Bumper
Right Bump
110L
110R

FIG. 3E

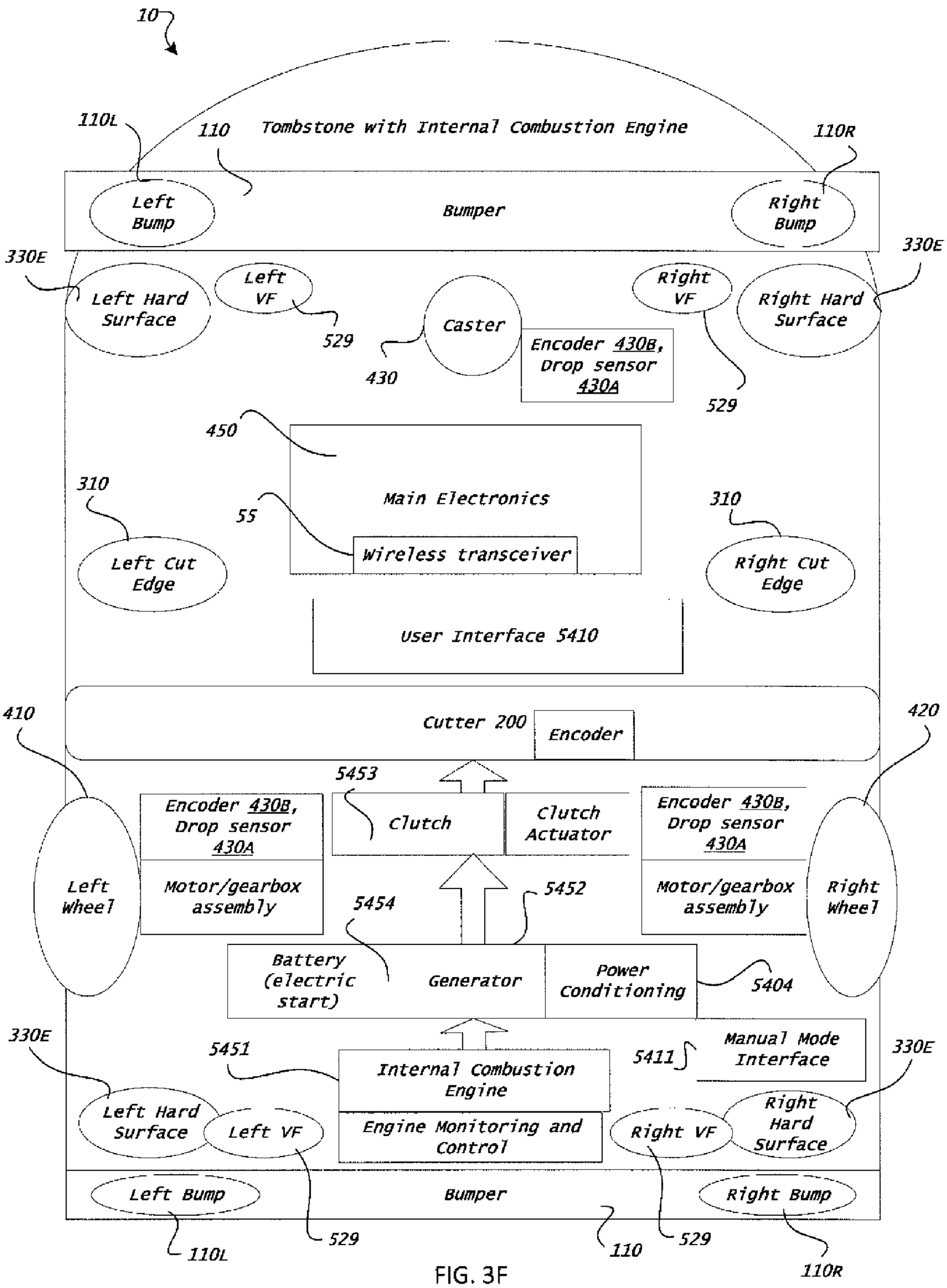

10
110L
110
Tombstone with Internal Combustion Engine
110R
Left Bump
Bumper
Right Bump
330E
330E
Left Hard Surface
Left VF
529
Caster
430
Encoder 430B, Drop sensor 430A
Right VF
529
Right Hard Surface
330E
450
Main Electronics
55
Wireless transceiver
310
Left Cut Edge
310
Right Cut Edge
User Interface 5410
410
Cutter 200
Encoder
420
5453
Encoder 430B, Drop sensor 430A
Clutch
Clutch Actuator
Encoder 430B, Drop sensor 430A
Left Wheel
Motor/gearbox assembly
5454
5452
Motor/gearbox assembly
Right Wheel
Battery (electric start)
Generator
Power Conditioning
5404
330E
5451
5411
Manual Mode Interface
330E
Internal Combustion Engine
Left Hard Surface
Left VF
Engine Monitoring and Control
Right VF
Right Hard Surface
Left Bump
Bumper
Right Bump
529
529
110
110L
110R

FIG. 3F

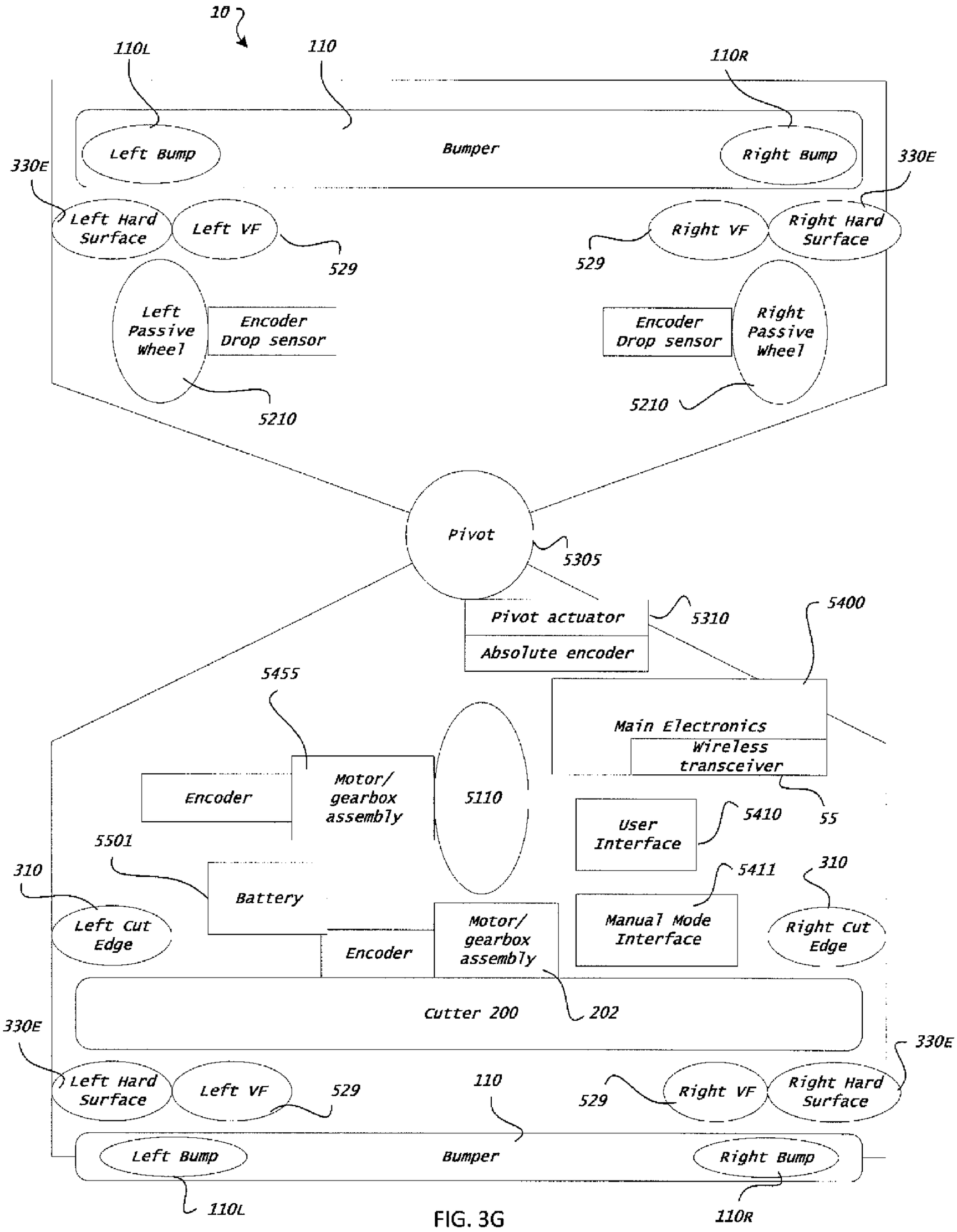

10
110L
110
110R
Left Bump
Bumper
Right Bump
330E
330E
Left Hard Surface
Left VF
529
Right VF
Right Hard Surface
529
Left Passive Wheel
Encoder Drop sensor
5210
Encoder Drop sensor
Right Passive Wheel
5210
Pivot
5305
Pivot actuator
5310
Absolute encoder
5400
5455
Main Electronics
Wireless transceiver
55
Encoder
Motor/ gearbox assembly
5110
5501
User Interface
5410
310
Battery
5411
310
Left Cut Edge
Encoder
Motor/ gearbox assembly
Manual Mode Interface
Right Cut Edge
Cutter 200
202
330E
330E
Left Hard Surface
Left VF
529
110
529
Right VF
Right Hard Surface
Left Bump
Bumper
Right Bump
110L
110R

FIG. 3G

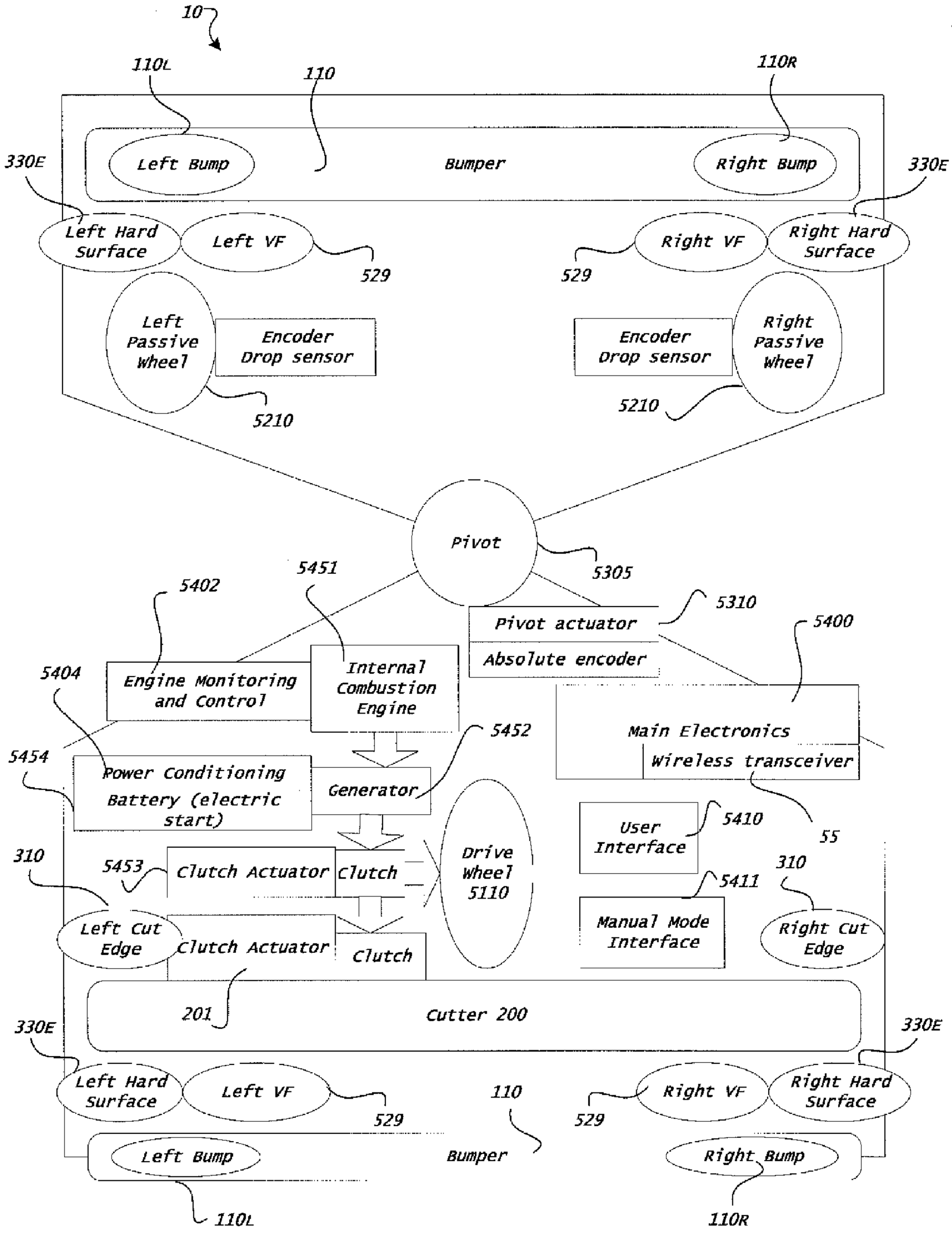

10
110L
110
110R
330E
Left Bump
Bumper
Right Bump
330E
Left Hard Surface
Left VF
529
Right VF
Right Hard Surface
529
Left Passive Wheel
Encoder Drop sensor
5210
Encoder Drop sensor
Right Passive Wheel
5210
Pivot
5305
5451
5402
5310
Pivot actuator
Absolute encoder
5400
5404
Engine Monitoring and Control
Internal Combustion Engine
5452
5454
Power Conditioning Battery (electric start)
Generator
Main Electronics
Wireless transceiver
55
User Interface
5410
310
5453
Clutch Actuator
Clutch
Drive Wheel 5110
5411
310
Left Cut Edge
Clutch Actuator
Clutch
Manual Mode Interface
Right Cut Edge
201
Cutter 200
330E
330E
Left Hard Surface
Left VF
529
110
529
Right VF
Right Hard Surface
Left Bump
Bumper
Right Bump
110L
110R

FIG. 3H

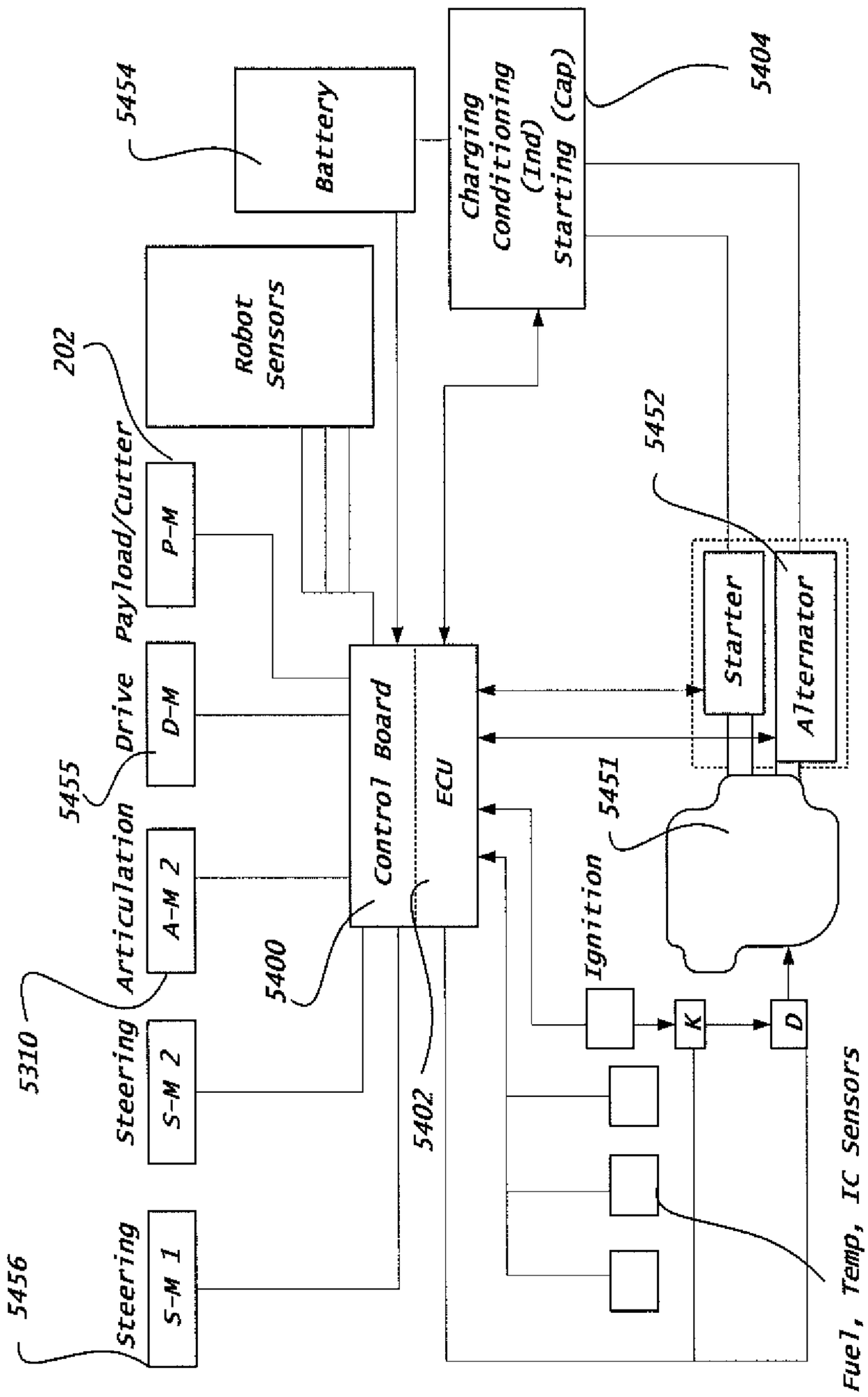

5454
Battery
Charging
Conditioning
(Ind)
Starting (Cap)
5404
Robot
Sensors
202
Payload/Cutter
P-M
Drive
D-M
5455
Articulation
A-M 2
5310
Steering
S-M 2
5456
Steering
S-M 1
5400
Control Board
ECU
5452
Starter
Alternator
5451
Ignition
K
D
5402
Fuel, Temp, IC Sensors

FIG. 3I

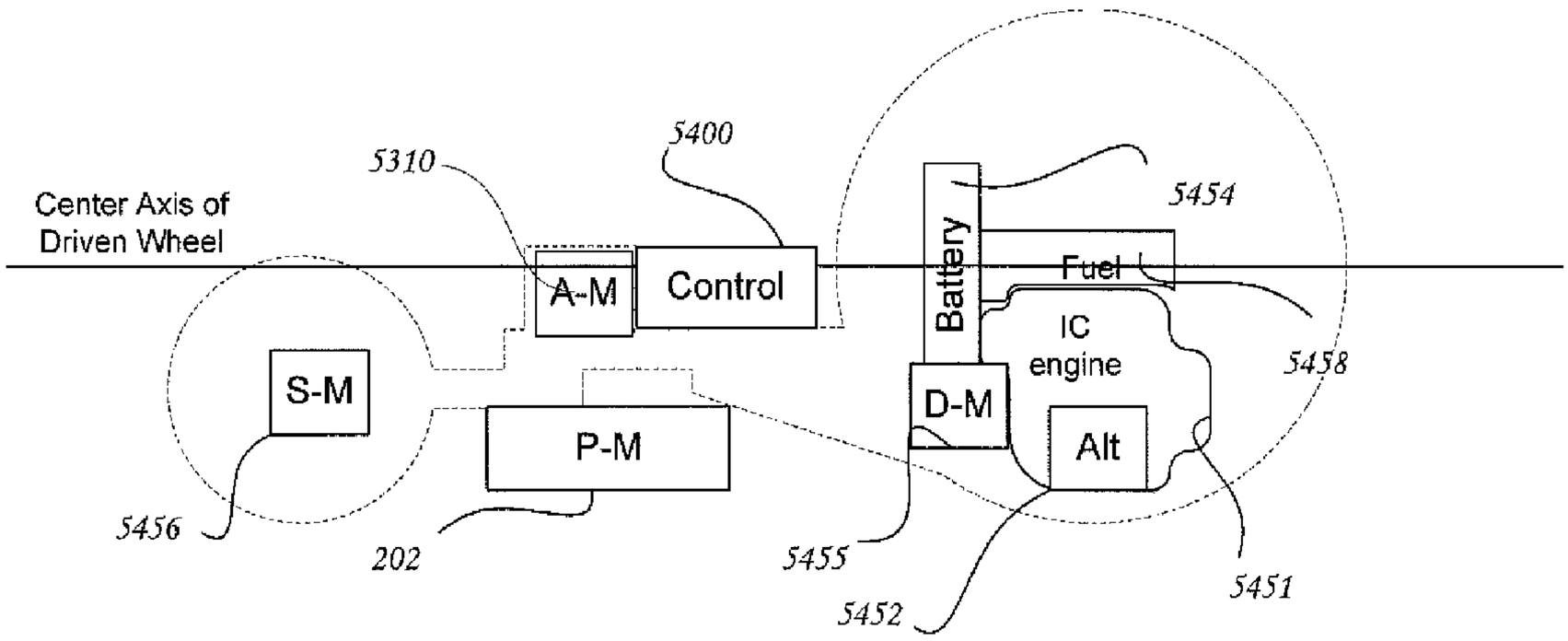

Center Axis of
Driven Wheel
5310
5400
5454
A-M
Control
Battery
Fuel
IC
engine
5458
S-M
D-M
P-M
Alt
5456
202
5455
5452
5451

FIG. 3J

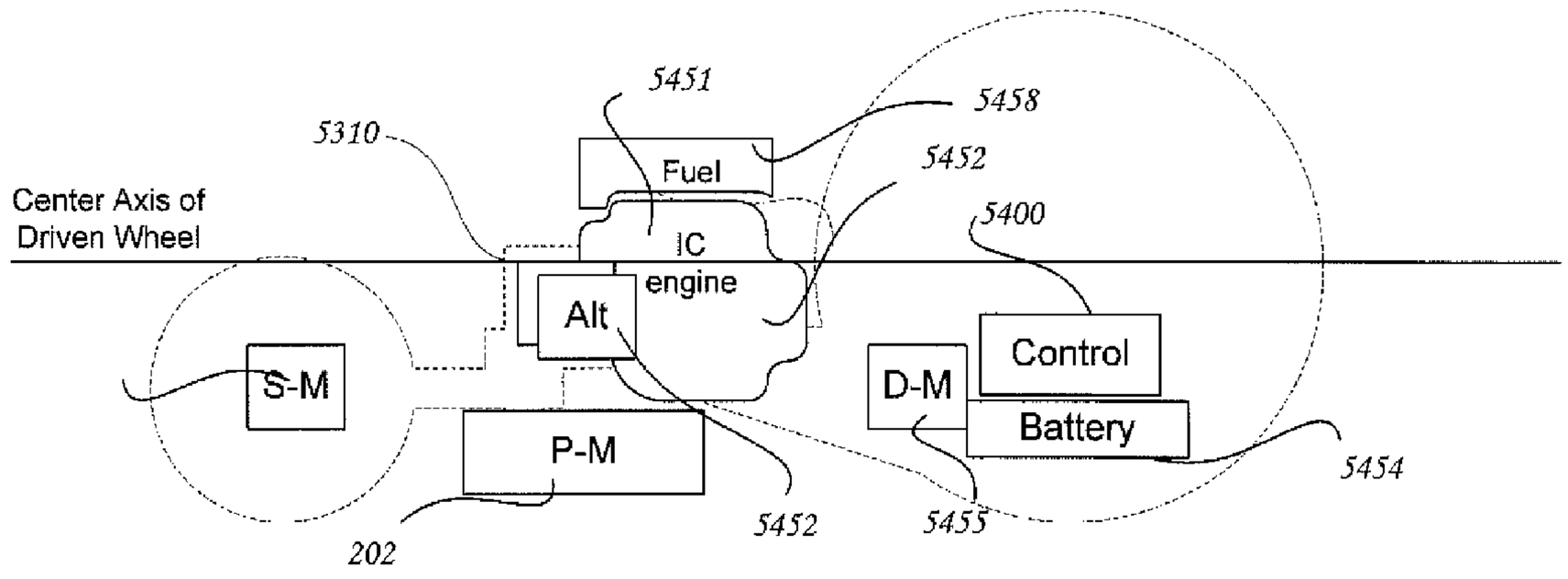

5451
5458
5310
Fuel
5452
Center Axis of
Driven Wheel
5400
IC
engine
Alt
Control
S-M
D-M
Battery
P-M
5454
202
5452
5455

FIG. 3K

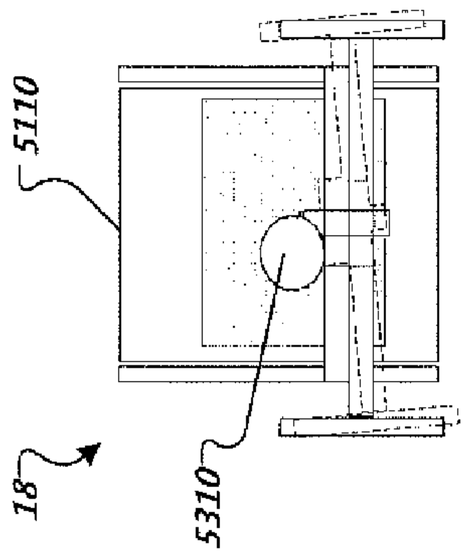


FIG. 4B

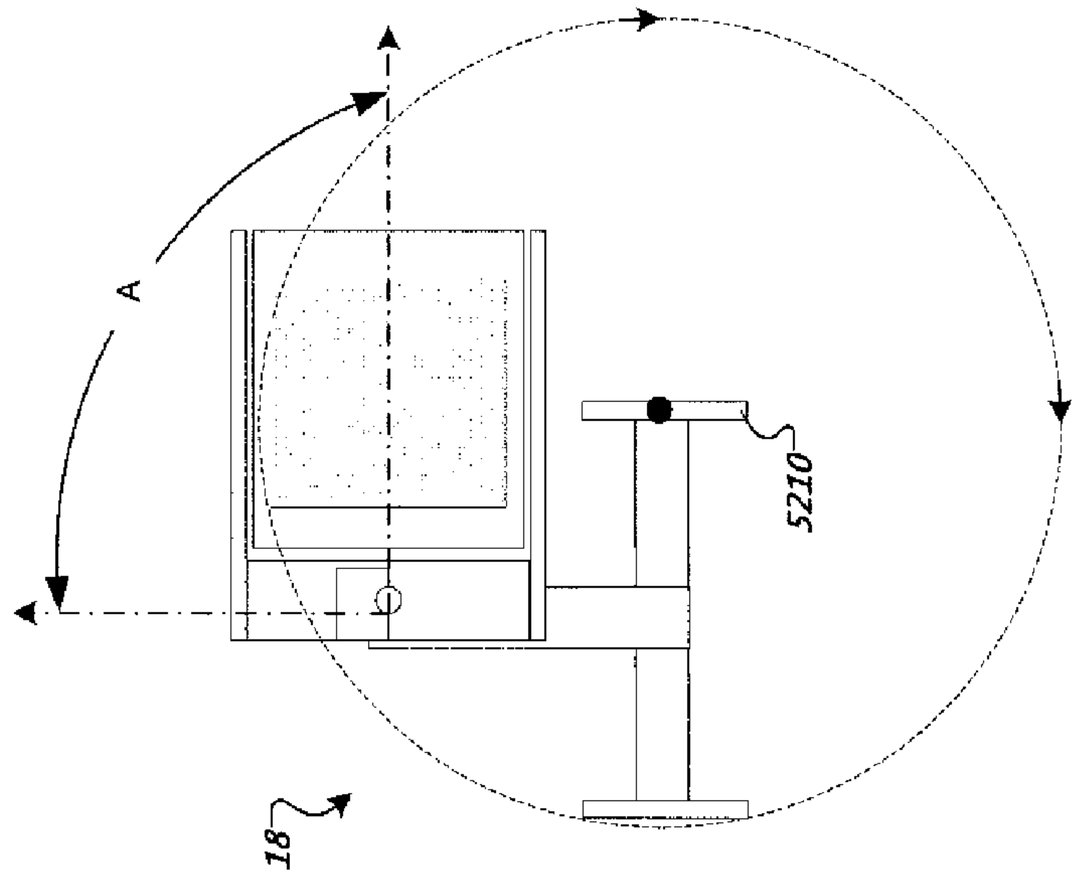


FIG. 4D

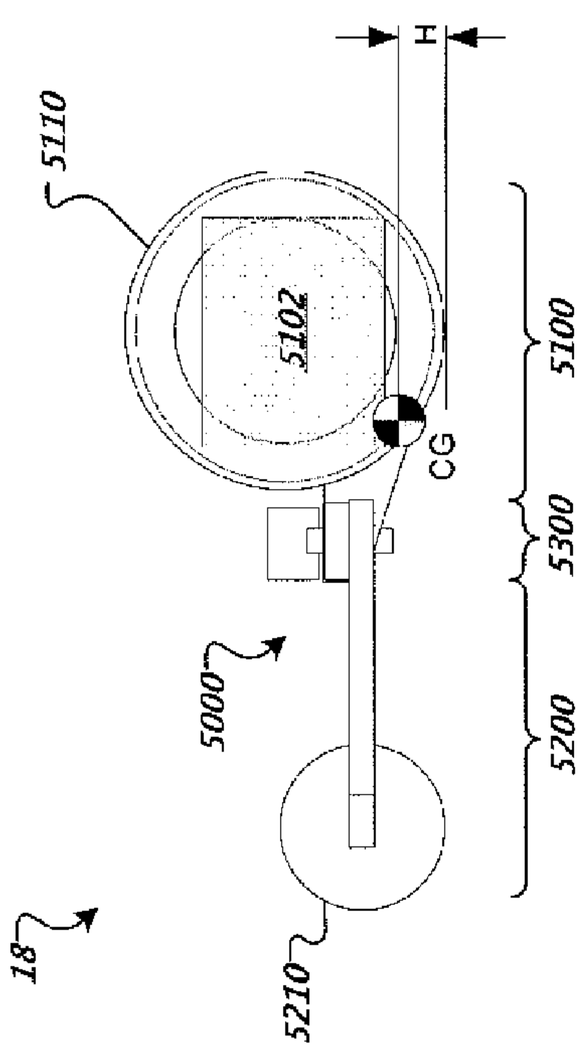


FIG. 4A

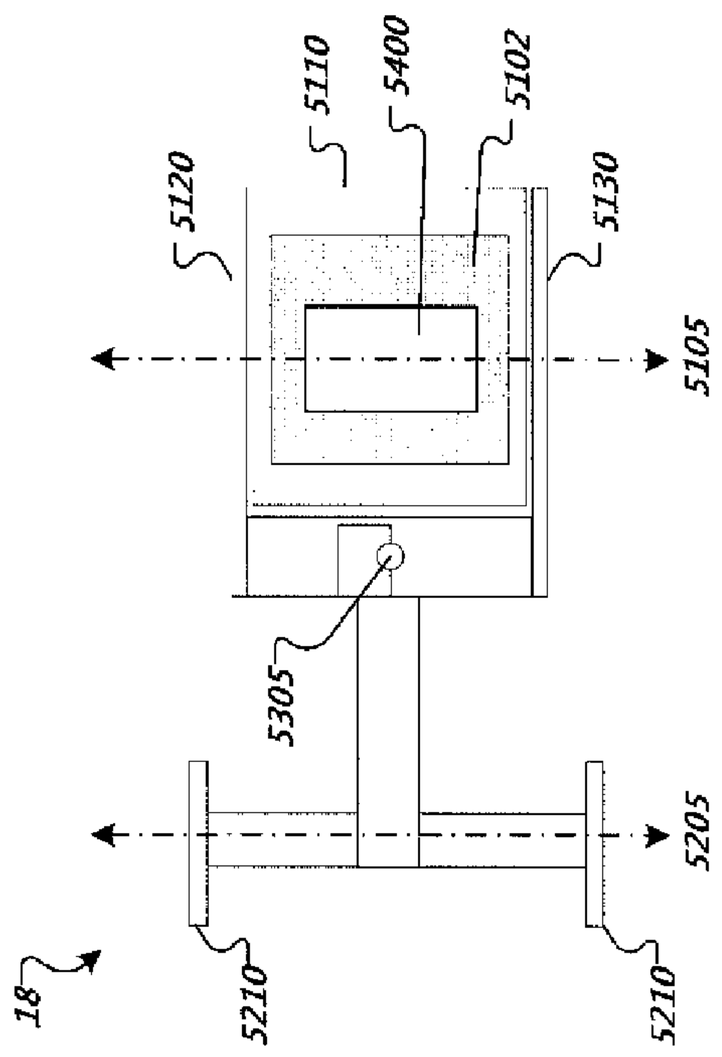


FIG. 4C

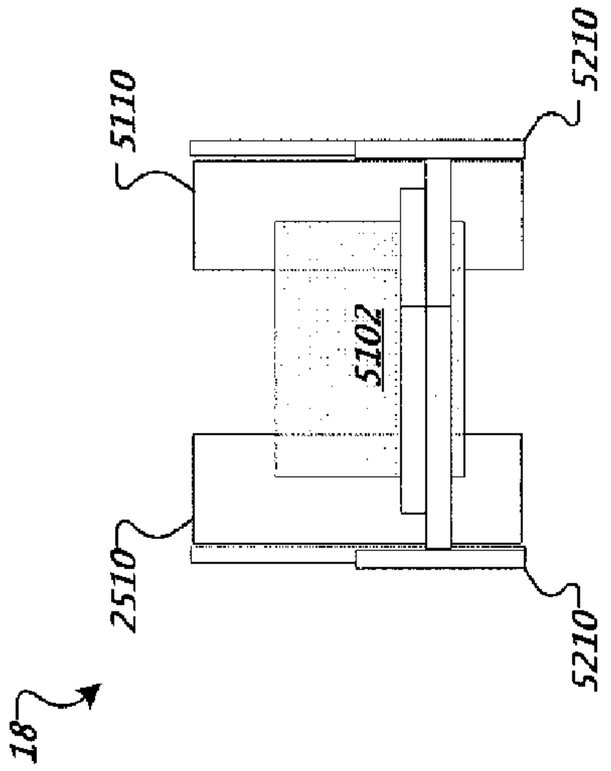


FIG. 4F

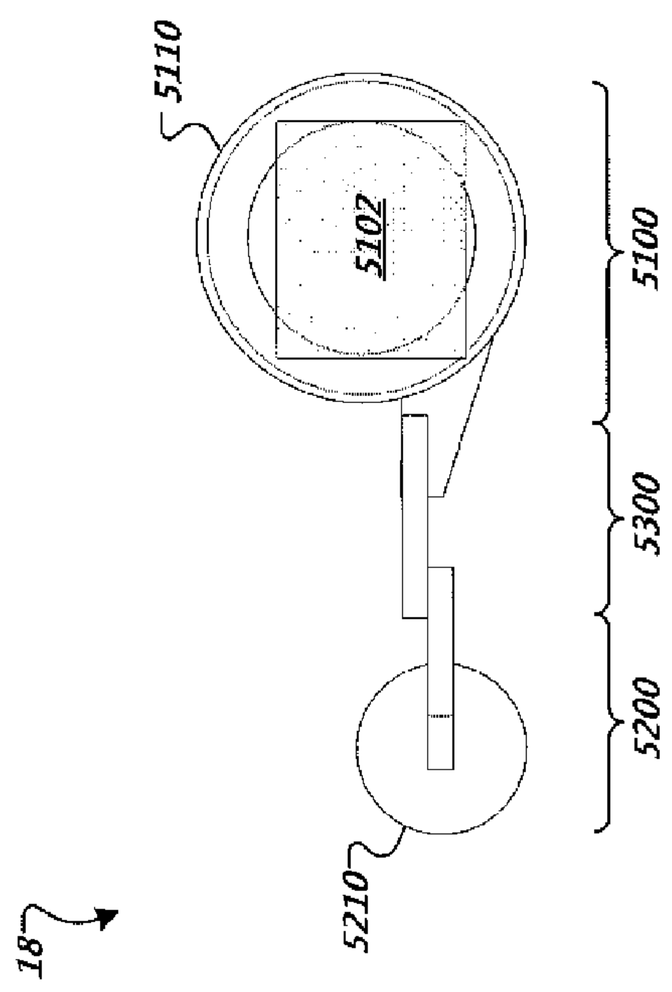


FIG. 4E

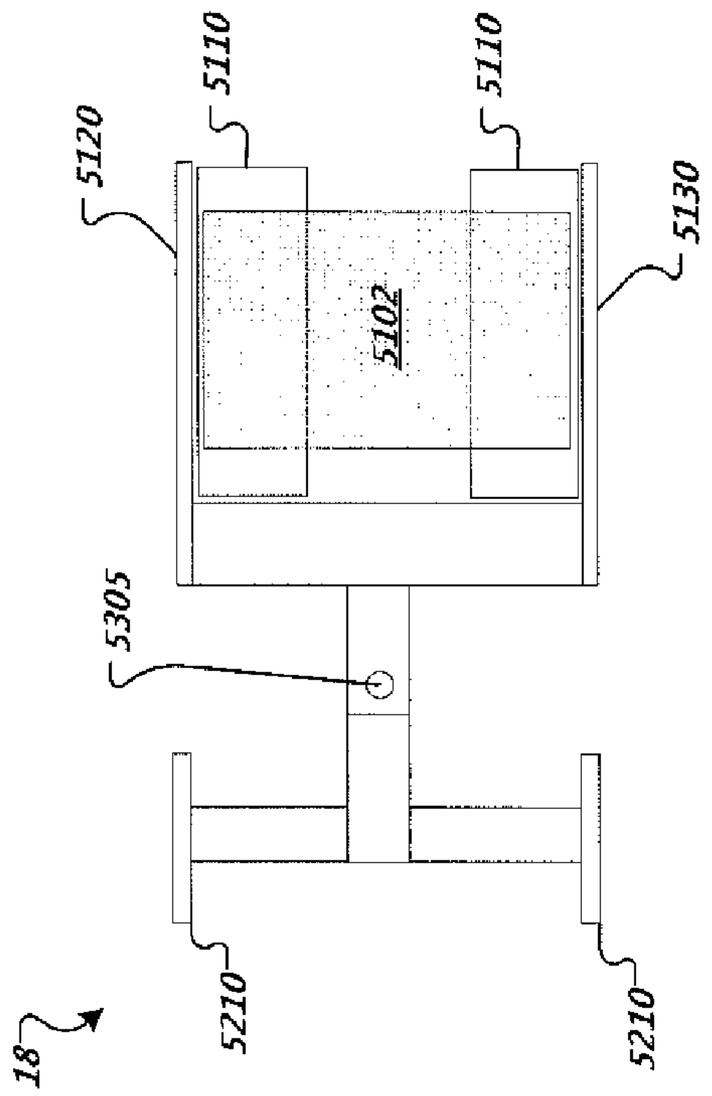


FIG. 4G

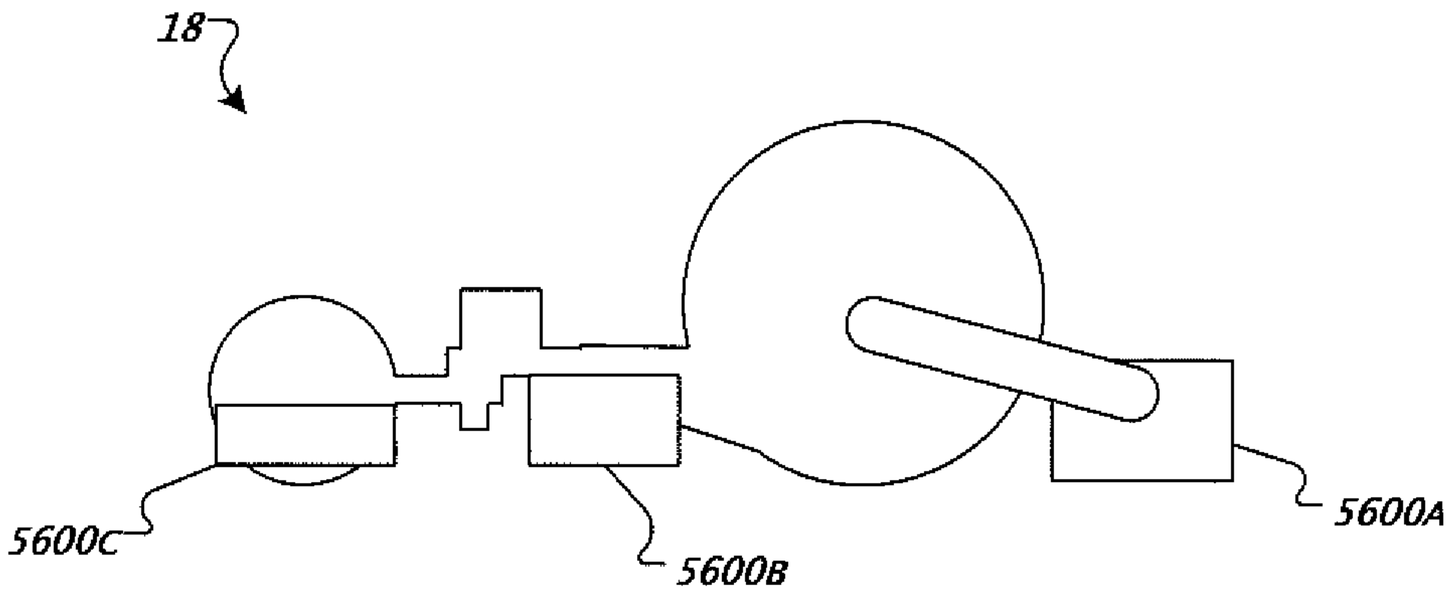


FIG. 4H

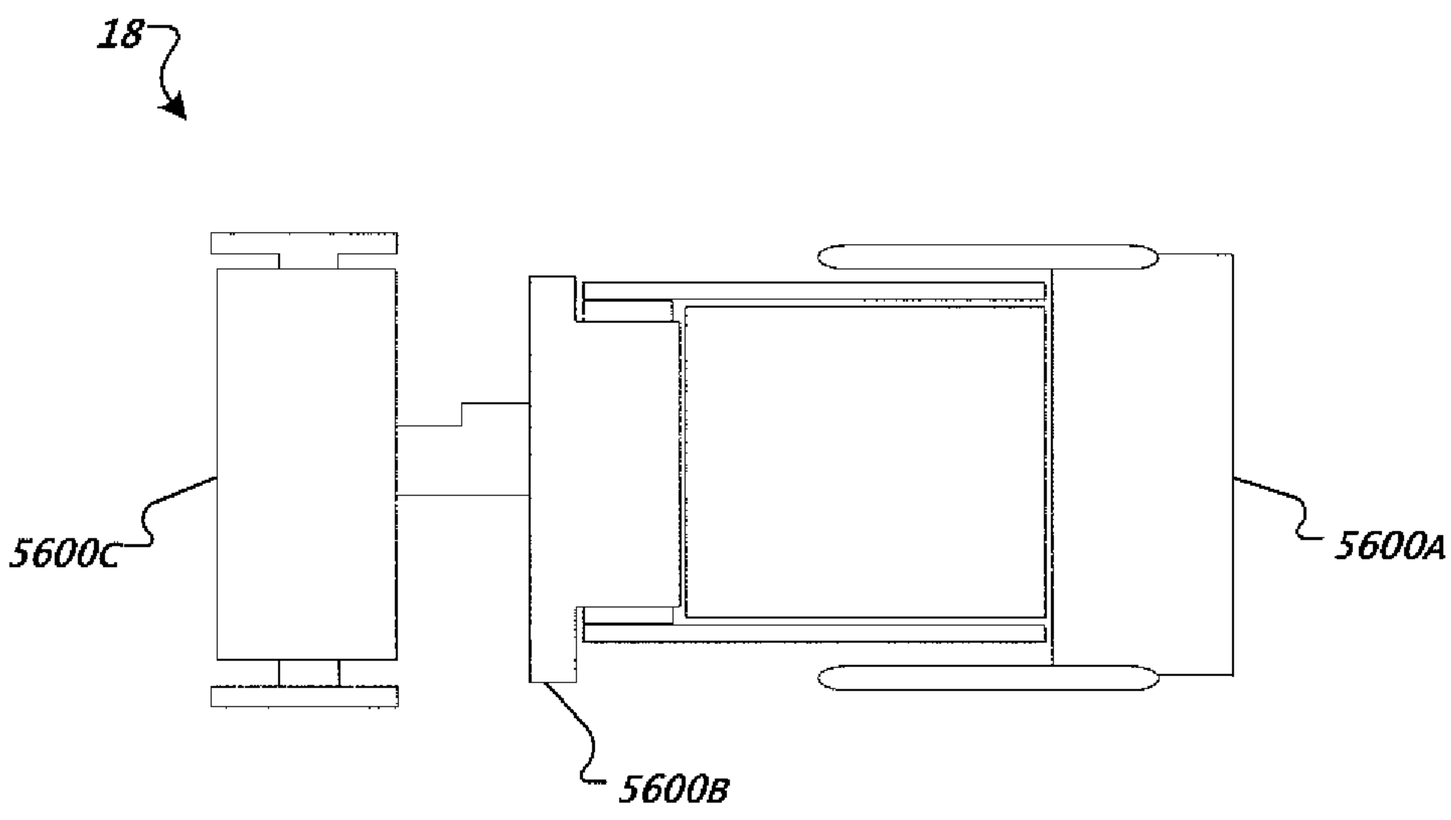


FIG. 4I

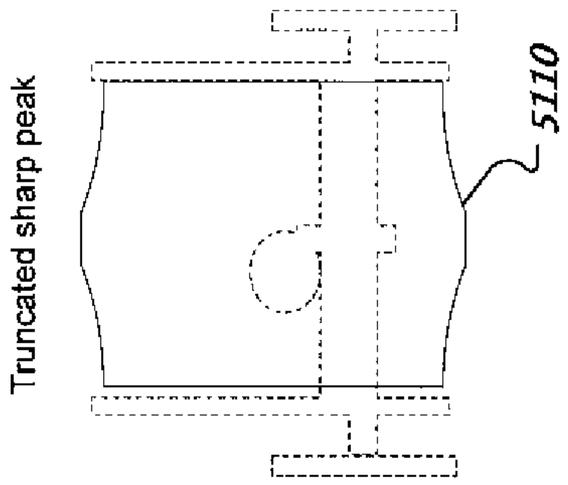


FIG. 4L

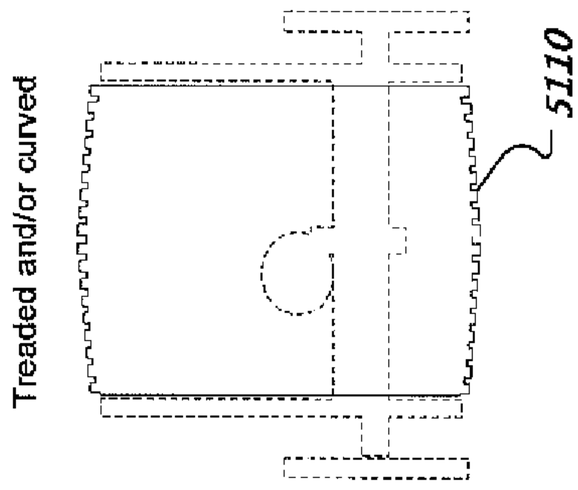


FIG. 4N

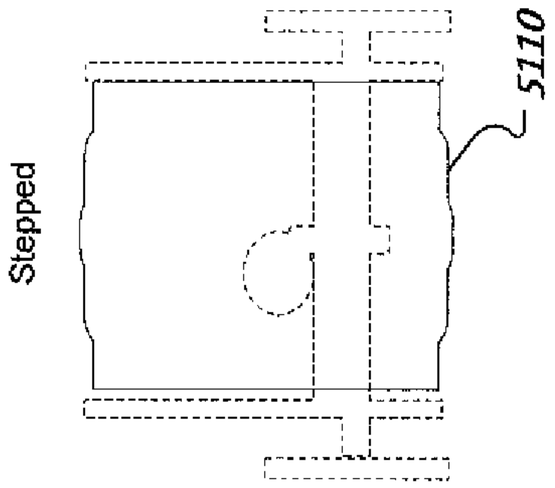


FIG. 4K

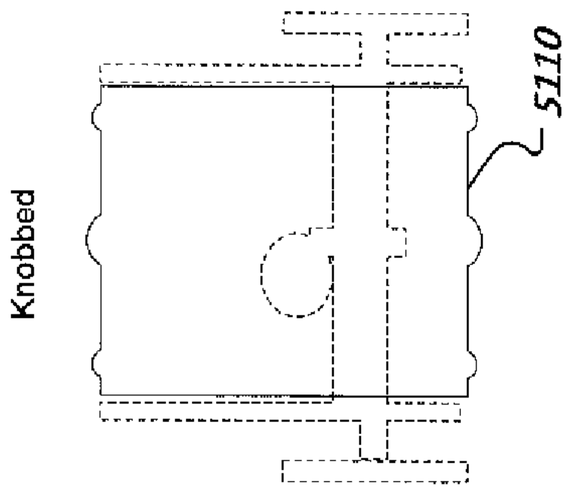


FIG. 4M

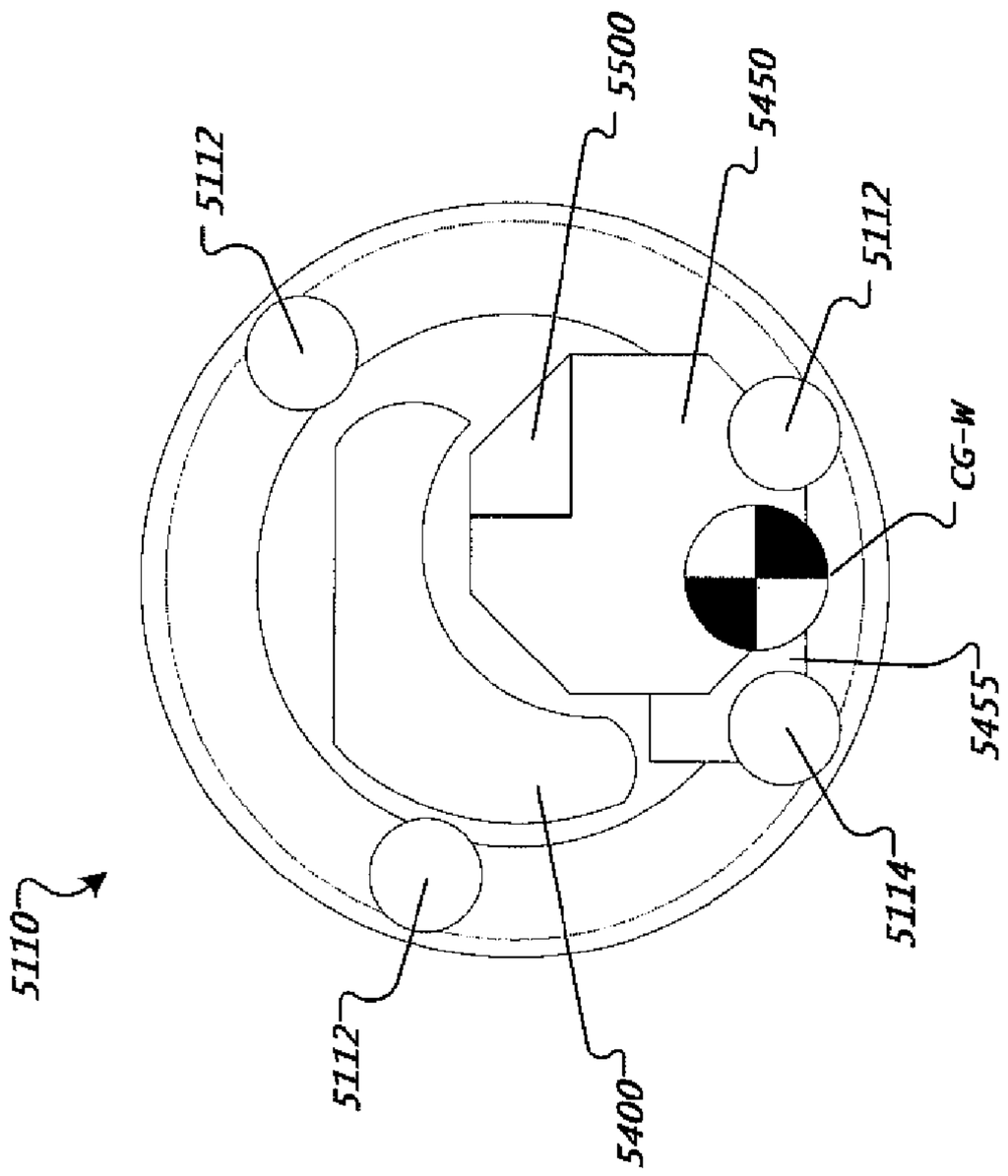


FIG. 4J

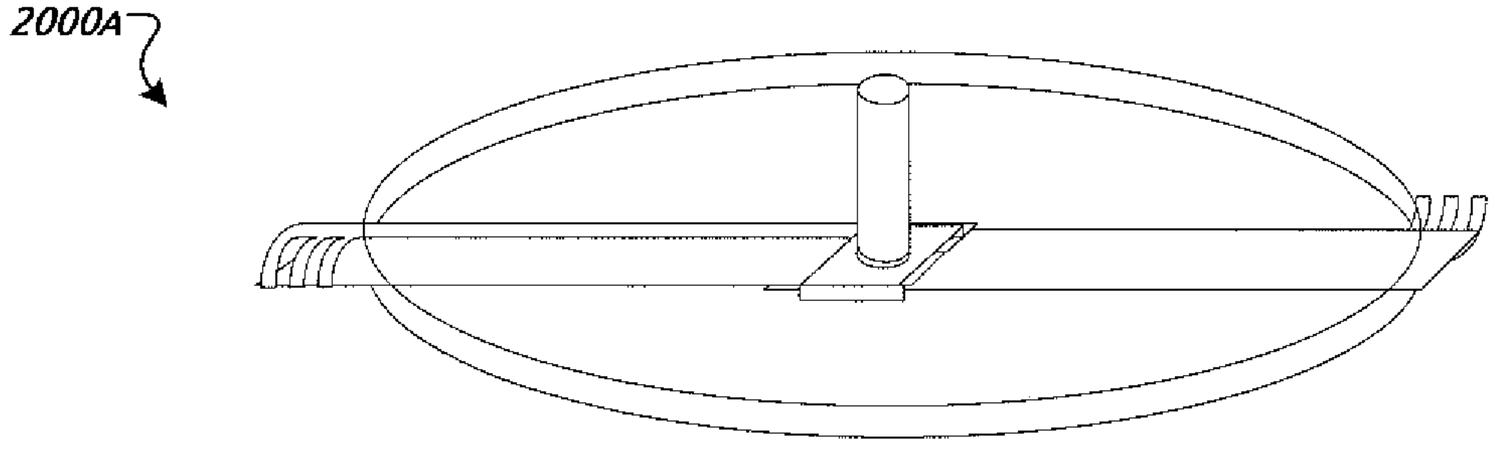


FIG. 5A

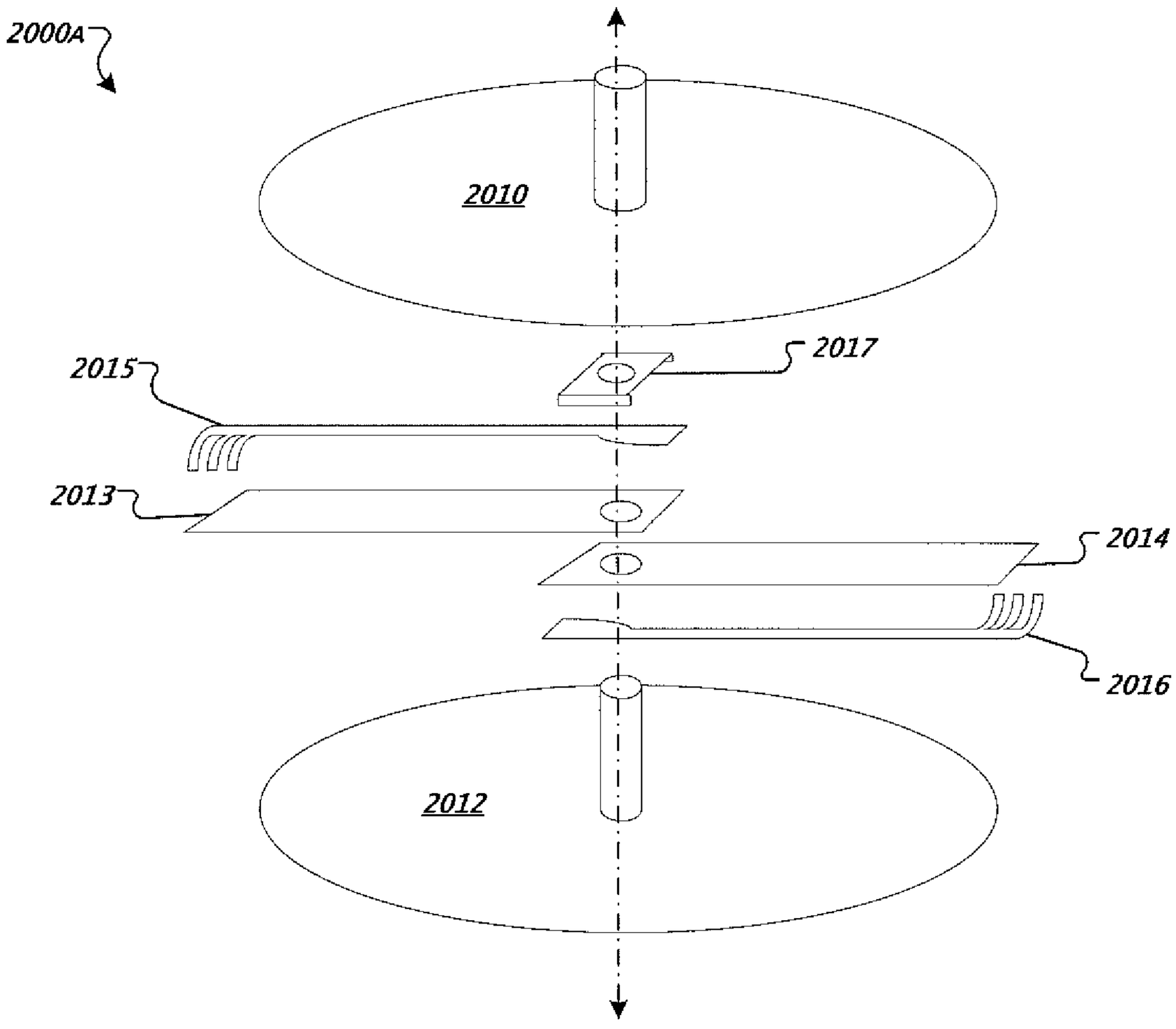


FIG. 5B

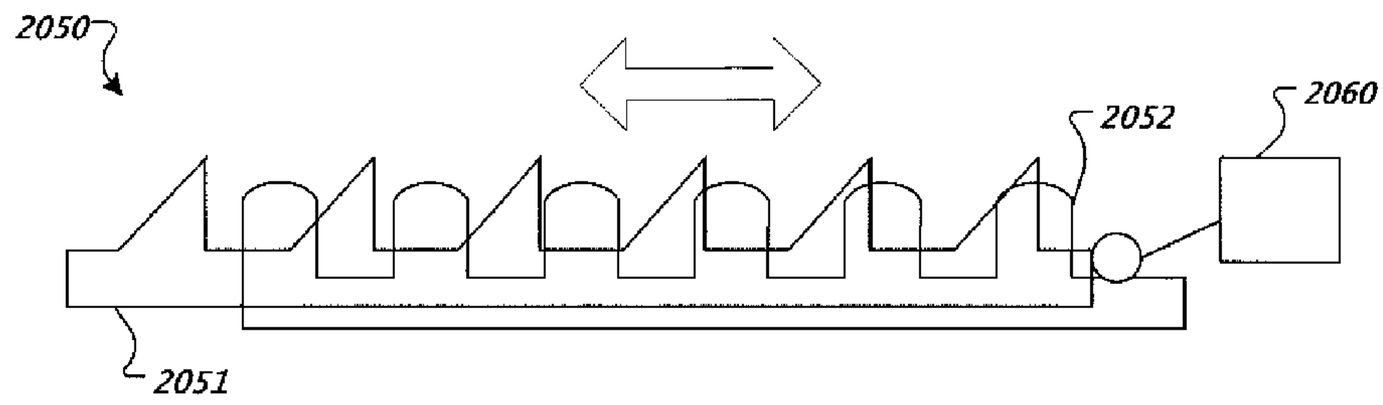


FIG. 5C

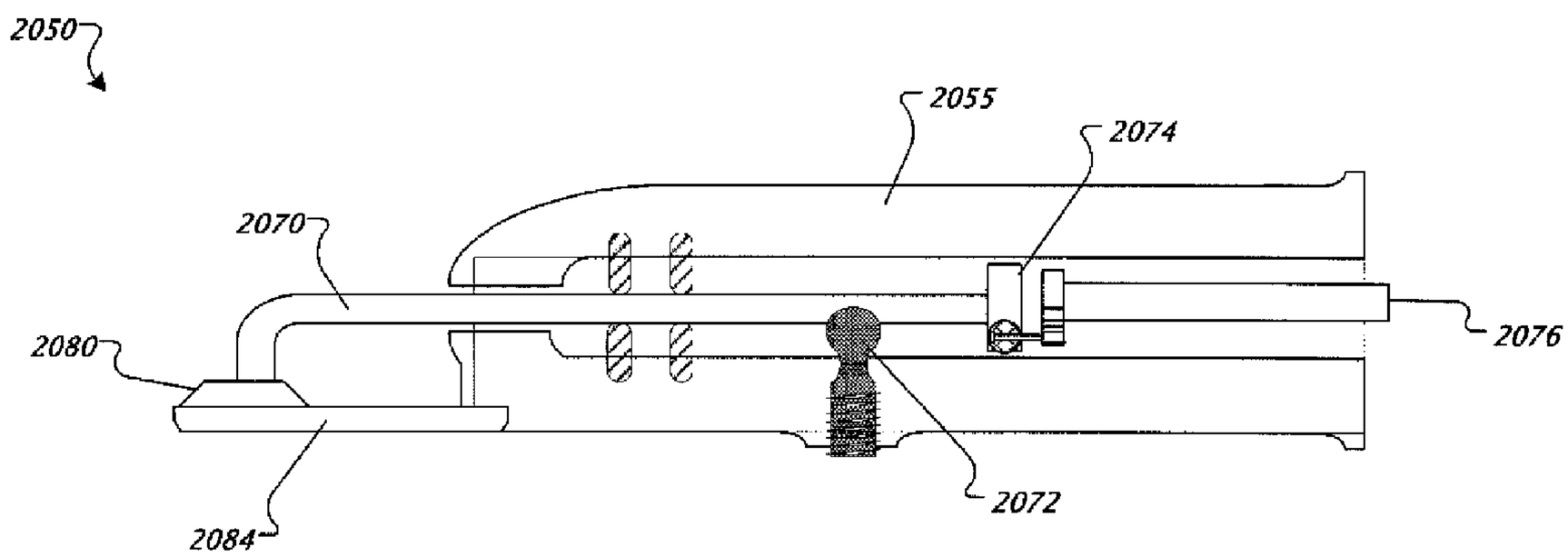


FIG. 5D

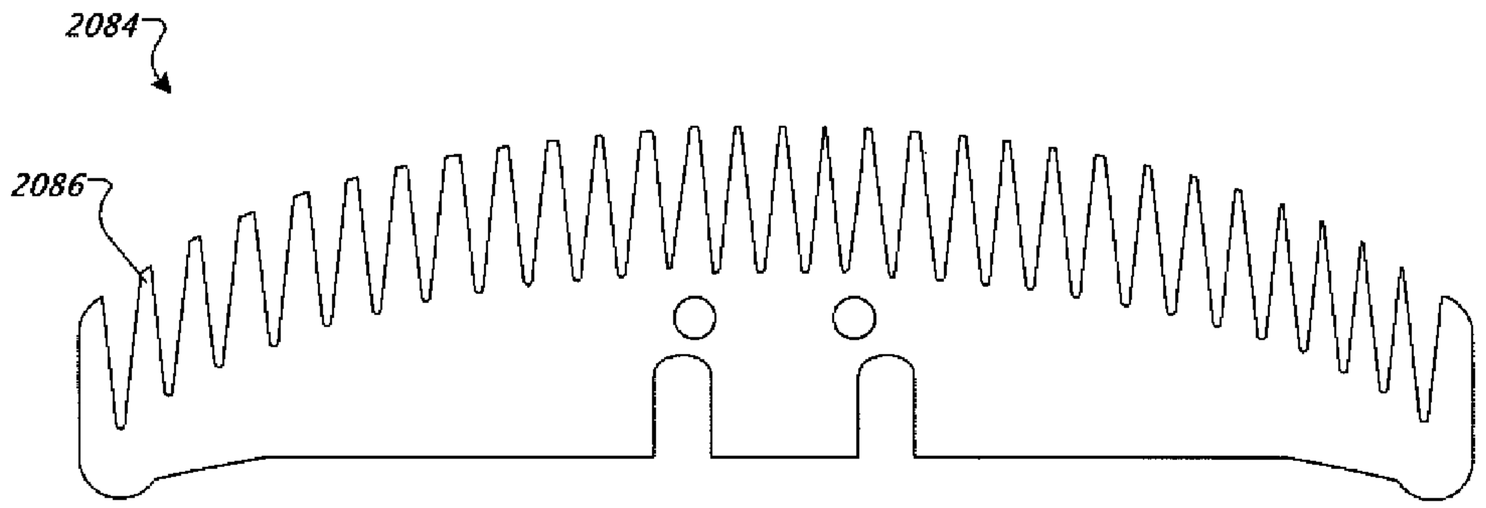


FIG. 5E

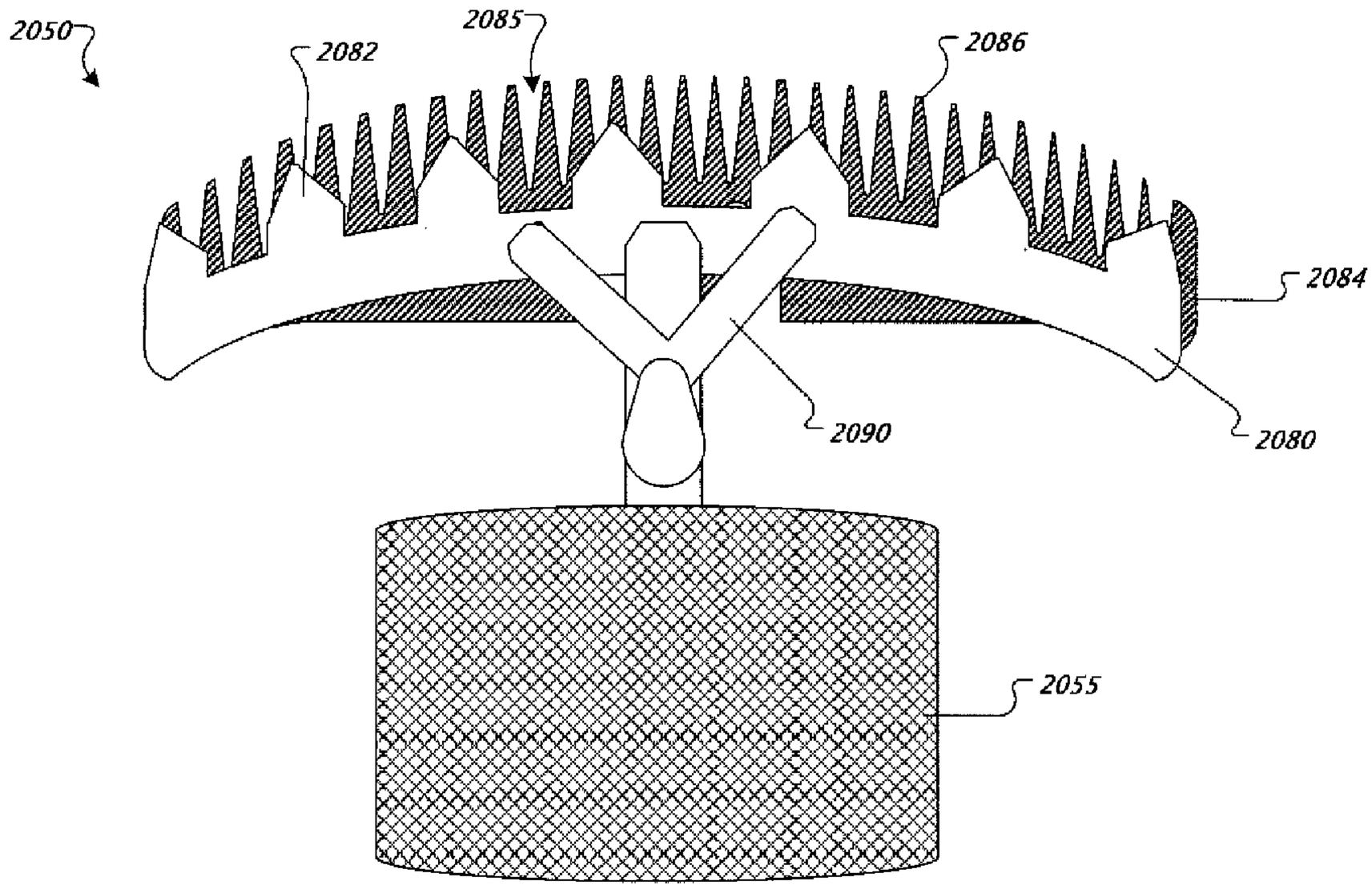

2050
2082
2085
2086
2084
2090
2080
2055

FIG. 5F

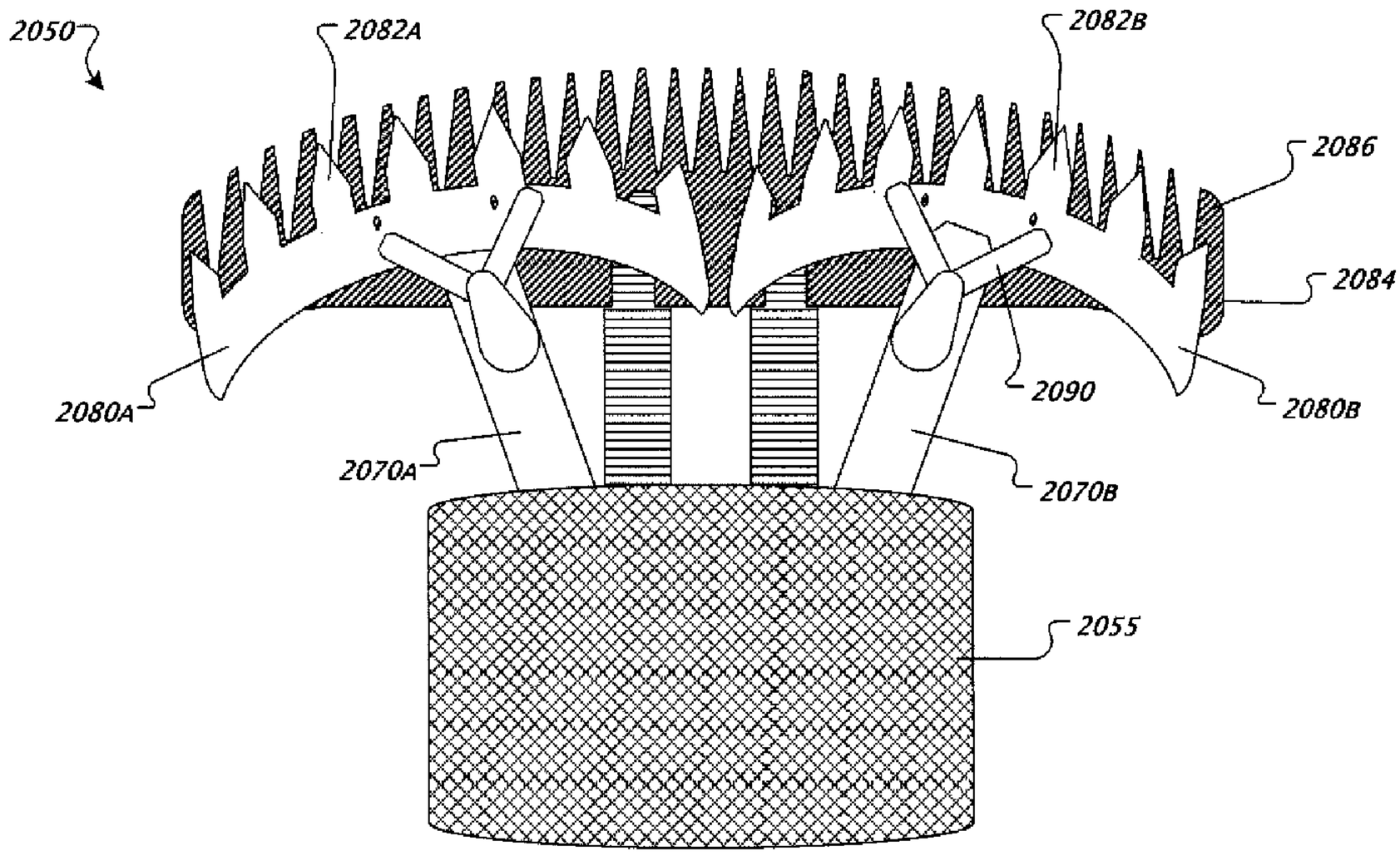

2050
2082A
2082B
2086
2084
2080A
2090
2080B
2070A
2070B
2055

FIG. 5G

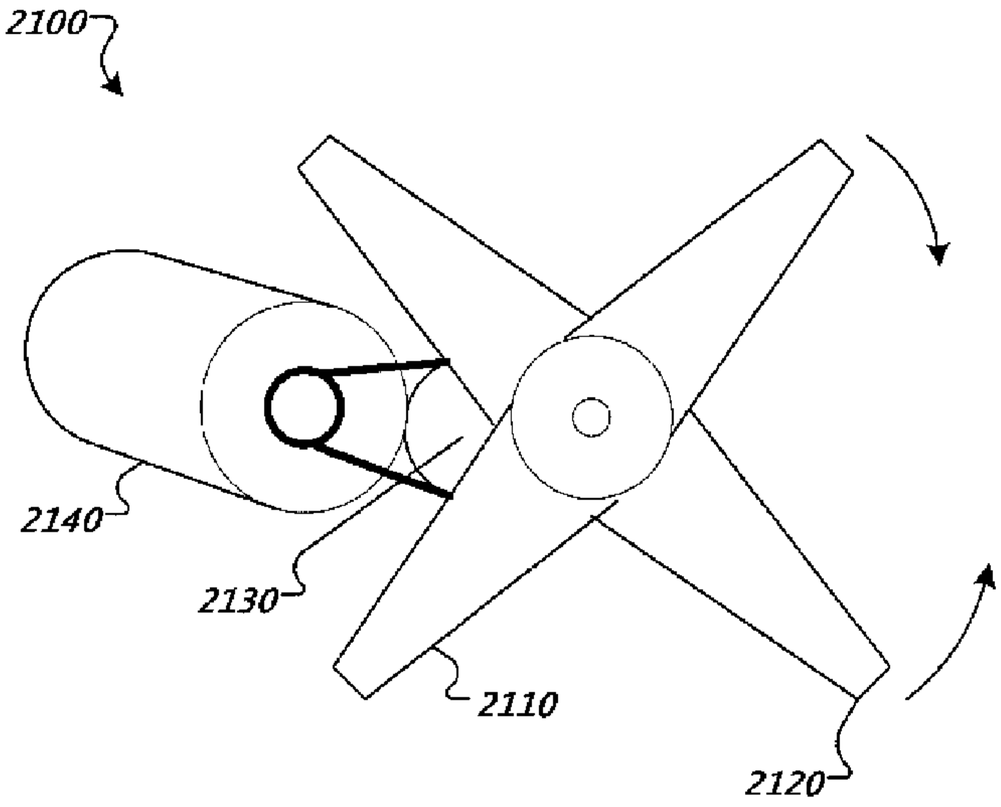


FIG. 5H

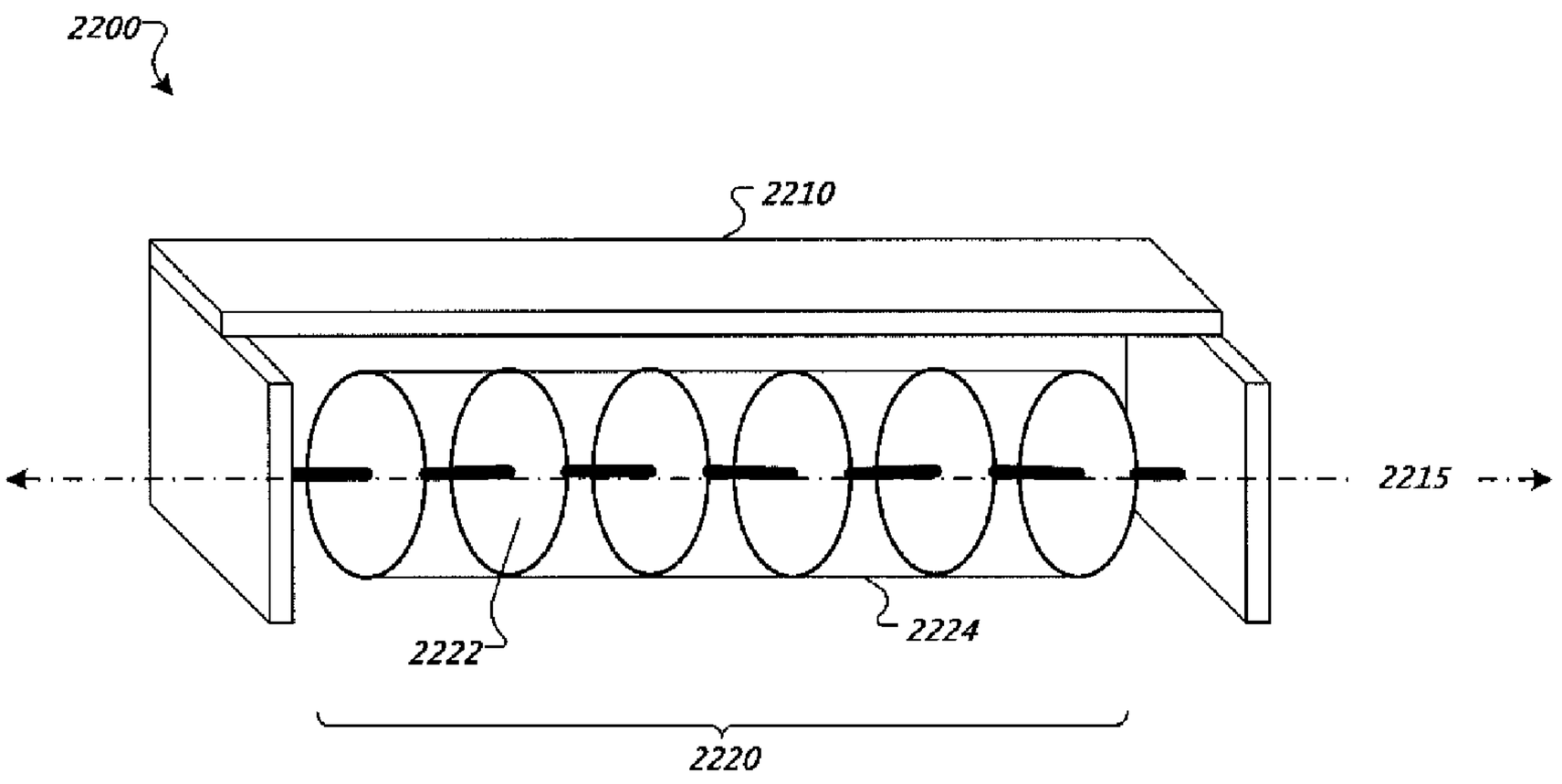


FIG. 5I

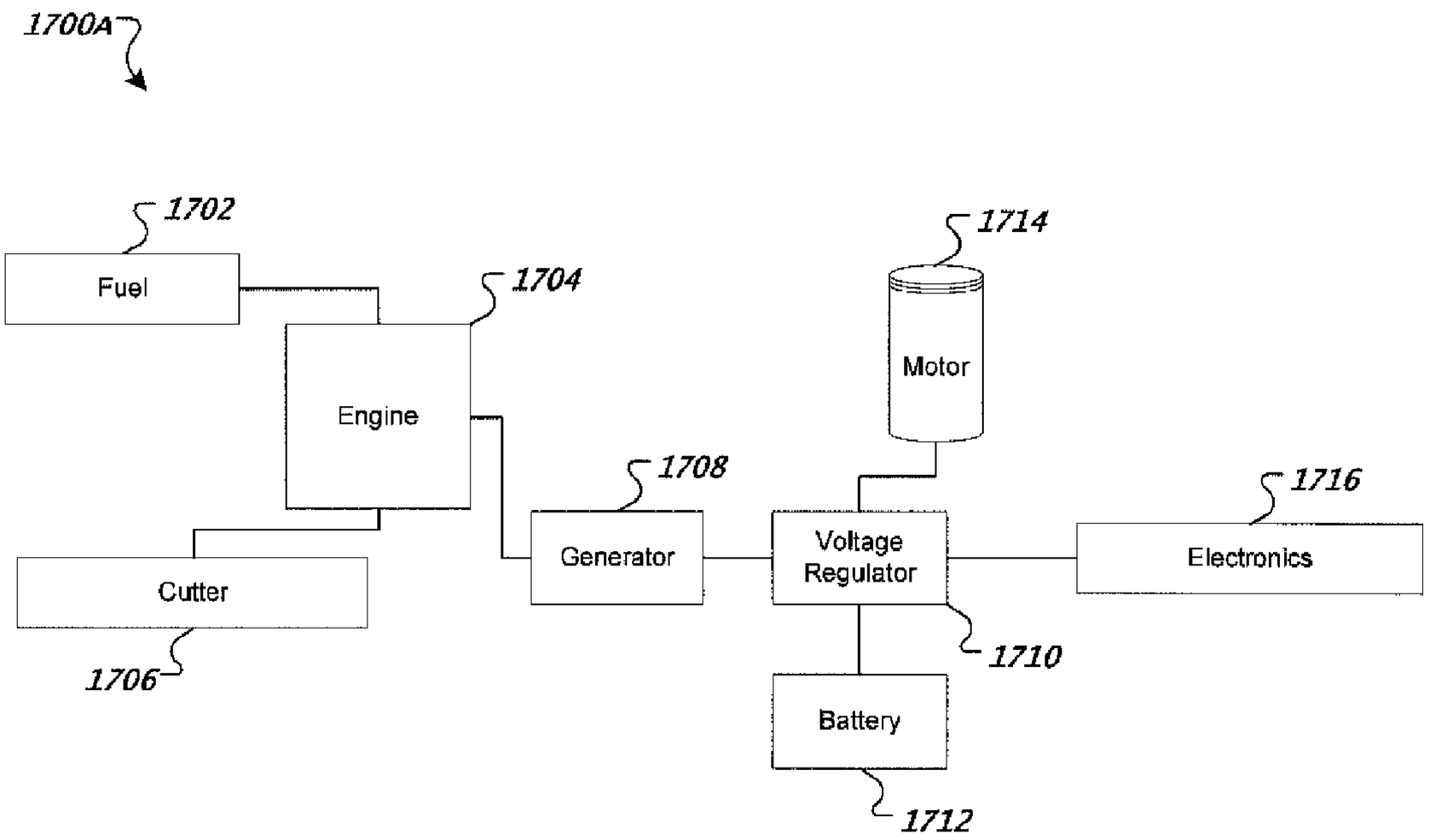

1700A
1702
Fuel
1704
Engine
1708
Generator
1714
Motor
1716
Voltage Regulator
Electronics
Cutter
1706
1710
Battery
1712

FIG. 6A

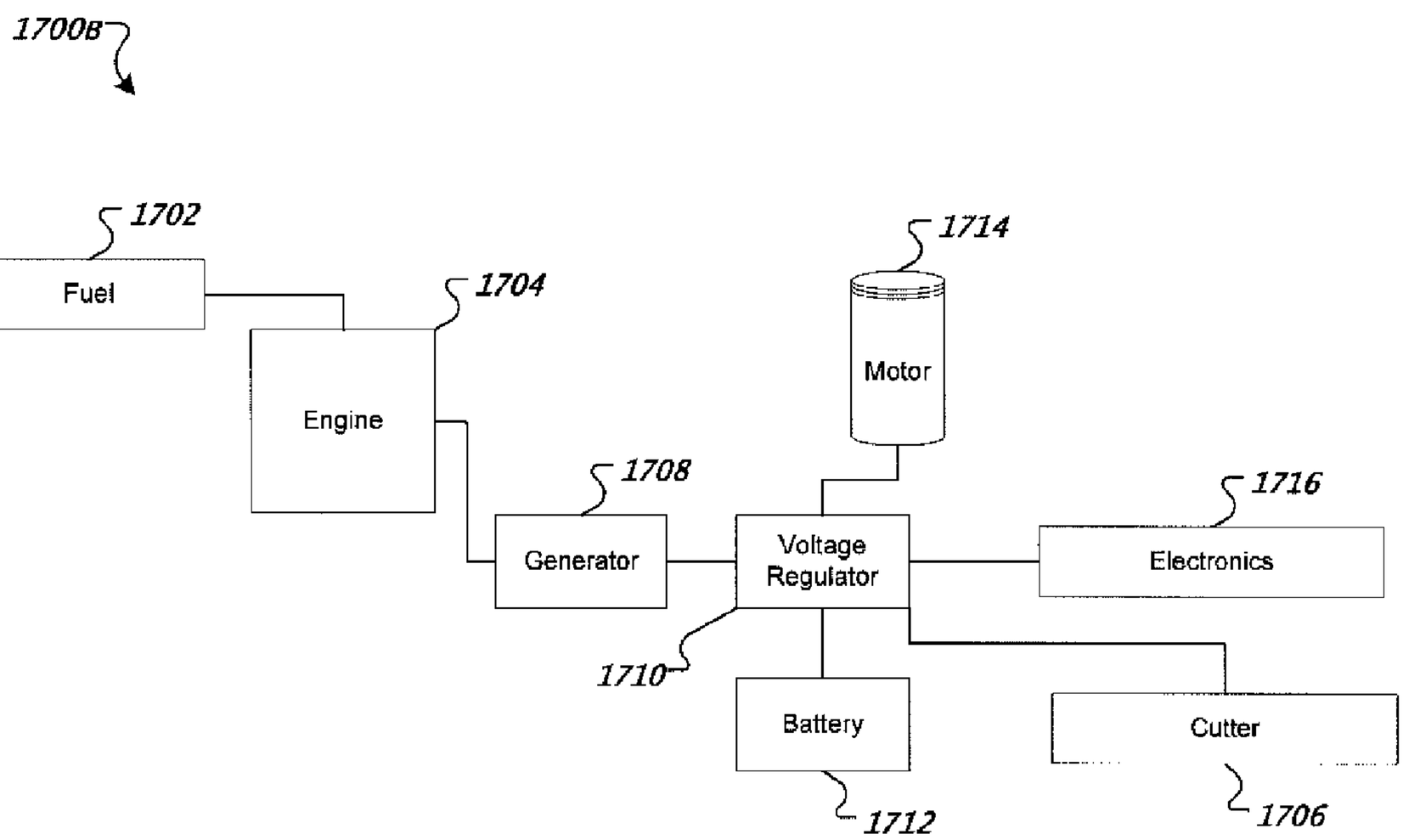

1700B
1702
Fuel
1704
Engine
1708
Generator
1714
Motor
1716
Voltage Regulator
Electronics
1710
Battery
Cutter
1712
1706

FIG. 6B

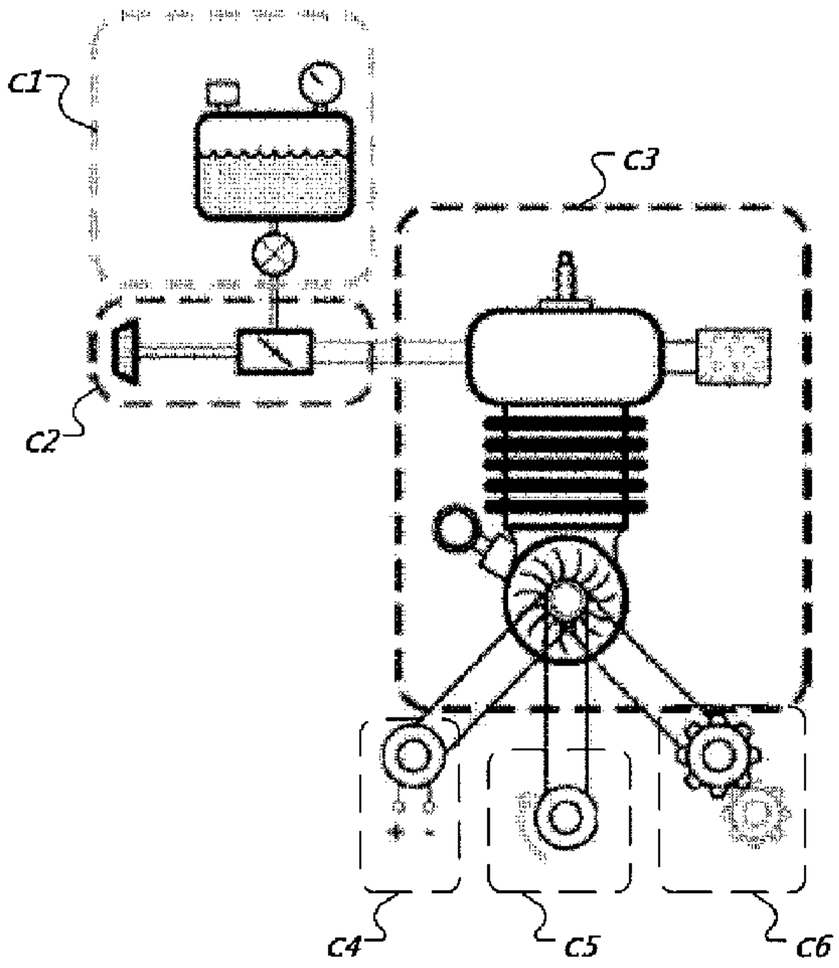


FIG. 6C

	C1 Fuel	C2 Intake	C3 Engine	C4 Electrical Output	C5 Starting	C6 Mechanical Output	
Expected System	• Tank • Vent with Breather • Tank Filter • Fuel Line • Fuel Valve	• Air Filter • Intake Tubing/ Manifold • Carburetor • Throttle • Choke	• Cylinder Head • Cylinder • Exhaust Muffler • Crank case • Output Shaft • Spark Plug • Spark Control Coil • Spark Control Magneto • Cooling System • Oil System	• Alternator / Generator • Wires • CPU	• Electric Motor • Starting Relays • High amp Wires • Battery • Starting System Control • Battery Charge Circuit • Batty Volt Meter	• Output Shaft • Support Bearings • Coupler	Required
	• Fuel Level Sensor	• Active Throttle Control • Air Filter Sensing • Active Choke Control	• Crank Velocity Sensor • Oil Level Sensor	• Rectifiers • Voltage Sensor • Battery		• Clutch • Speed Sensor	Optional
	• Fuel Pump • Fuel Pressuriz-ation • Fuel Pressure Sender	• Fuel Injection • Pressure Sensors • Temp Sensors • Throttle Position Sensor	• Active Spark Control • Crank Position Sensor • Temp Sensors	• Voltage Regulator	• One-way Clutch • Pull-start Cord • Handle • Offset Drive System	• Transmission • Speed Reducer • Clutch Actuator • Direction Reverser • Load Sensor	

FIG. 6D

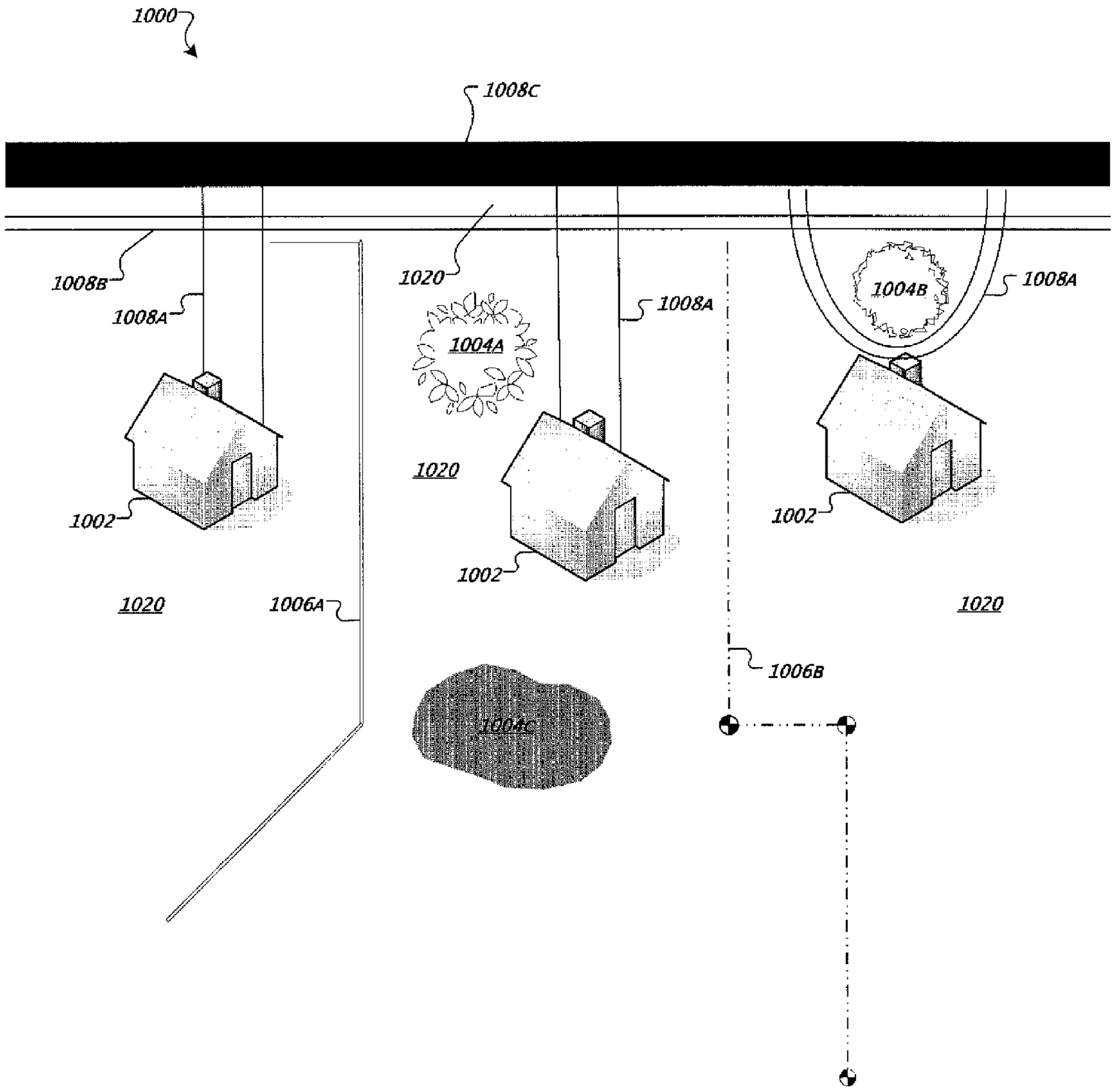

1000
1008C
1008B
1008A
1020
1004A
1008A
1004B
1008A
1002
1020
1002
1002
1020
1020
1006A
1004C
1006B

FIG. 6E

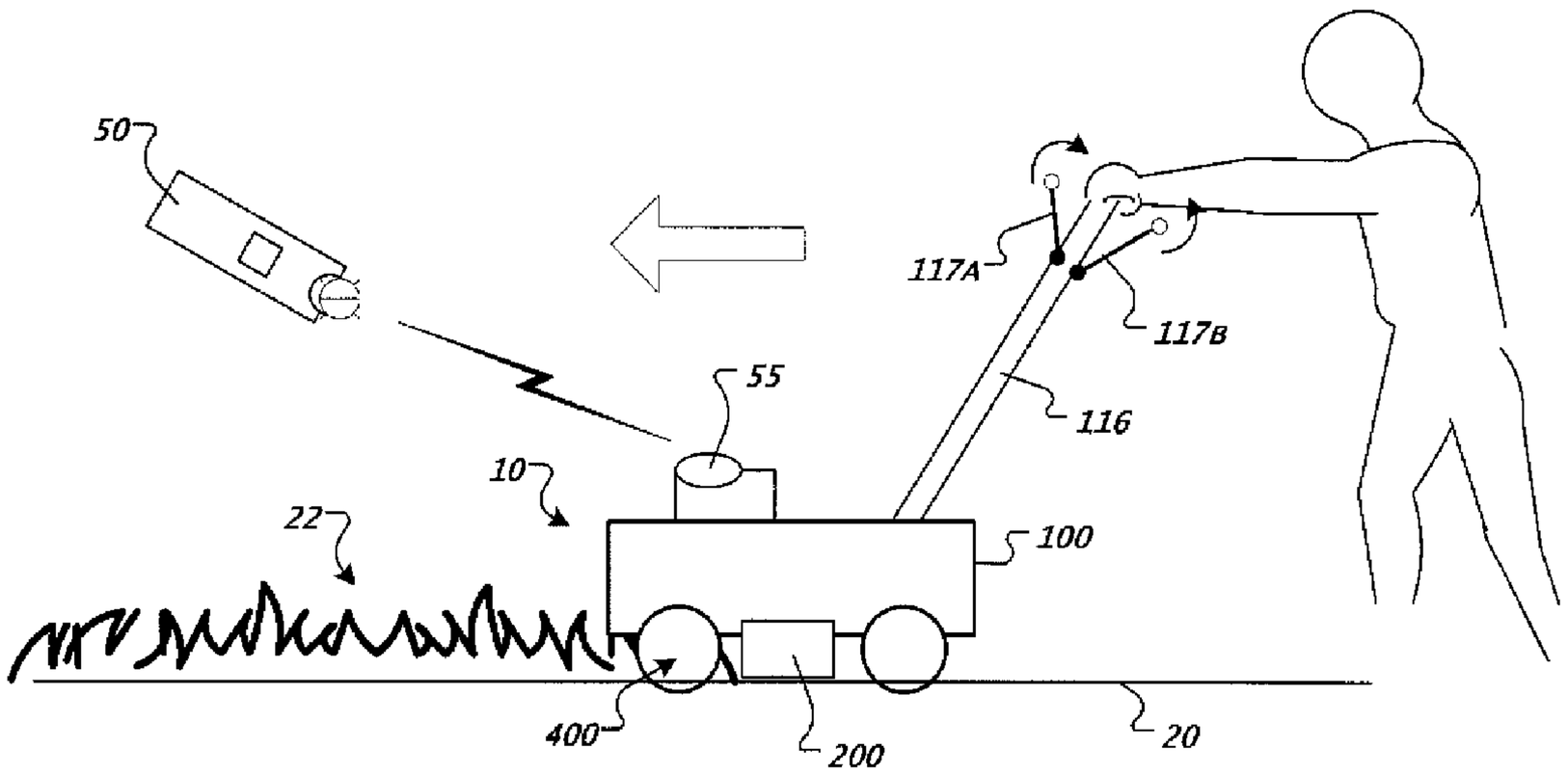

50
55
10
22
100
117A
117B
116
400
200
20

FIG. 7A

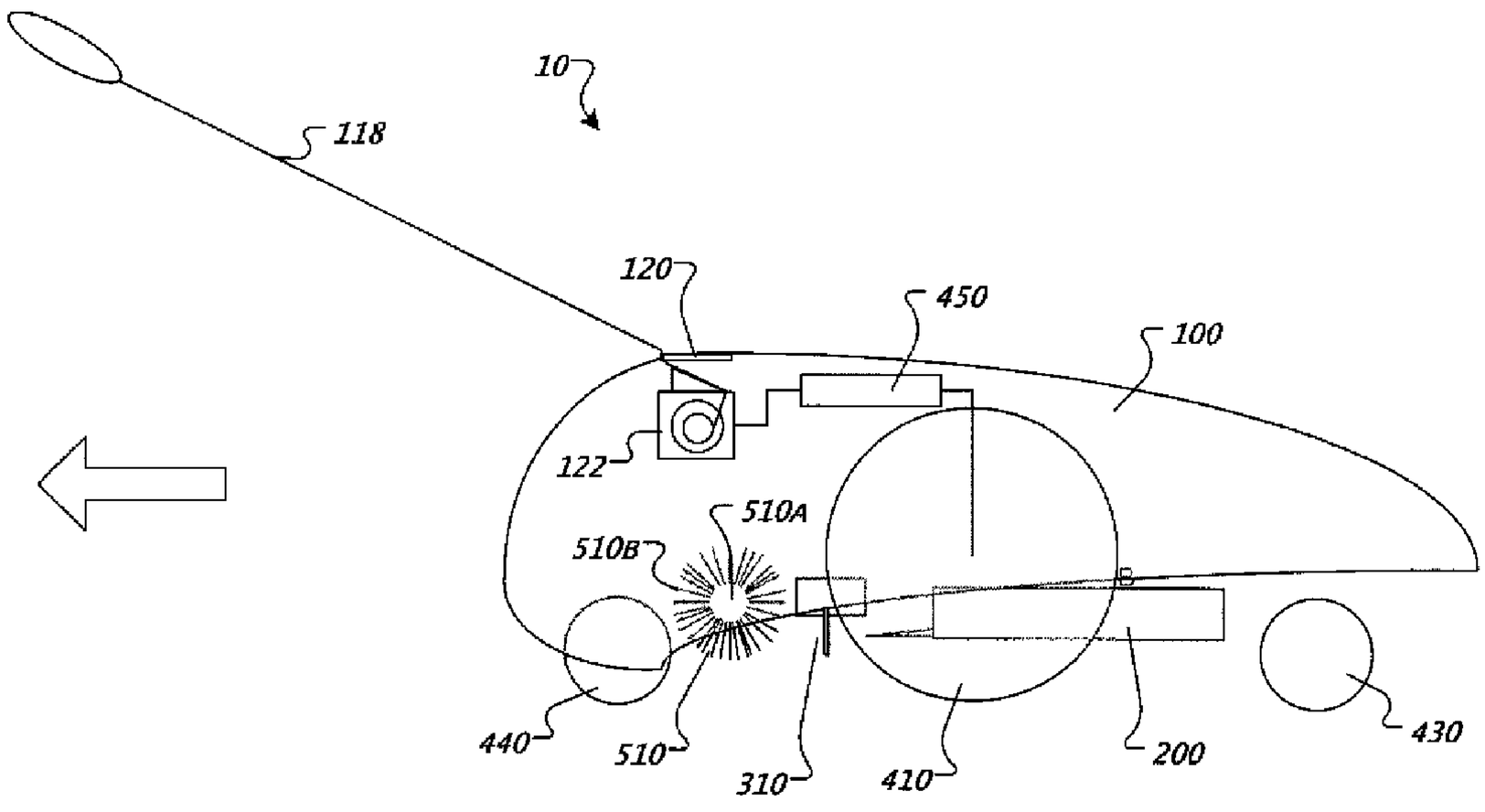
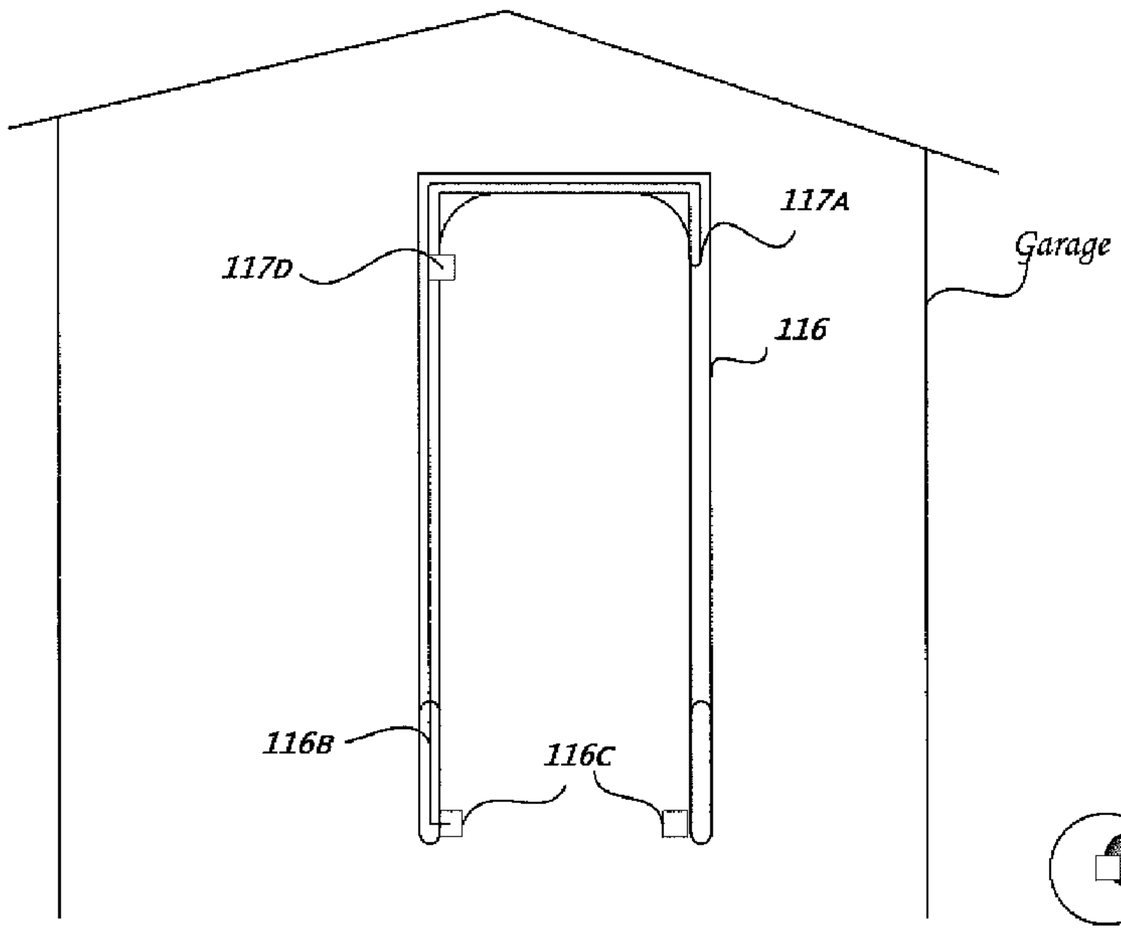

10
118
120
450
100
122
510A
510B
440
510
310
410
200
430

FIG. 7B


117A
117D
Garage
116
116B
116C

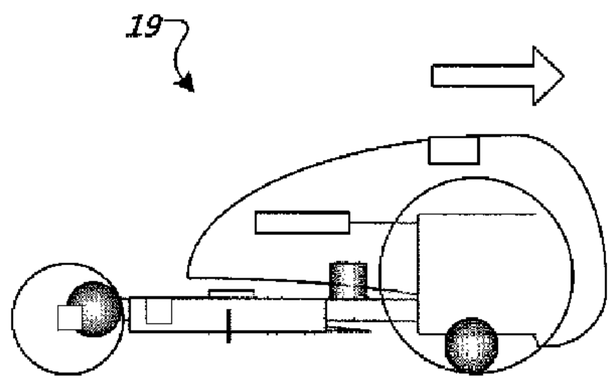

19

FIG. 7C

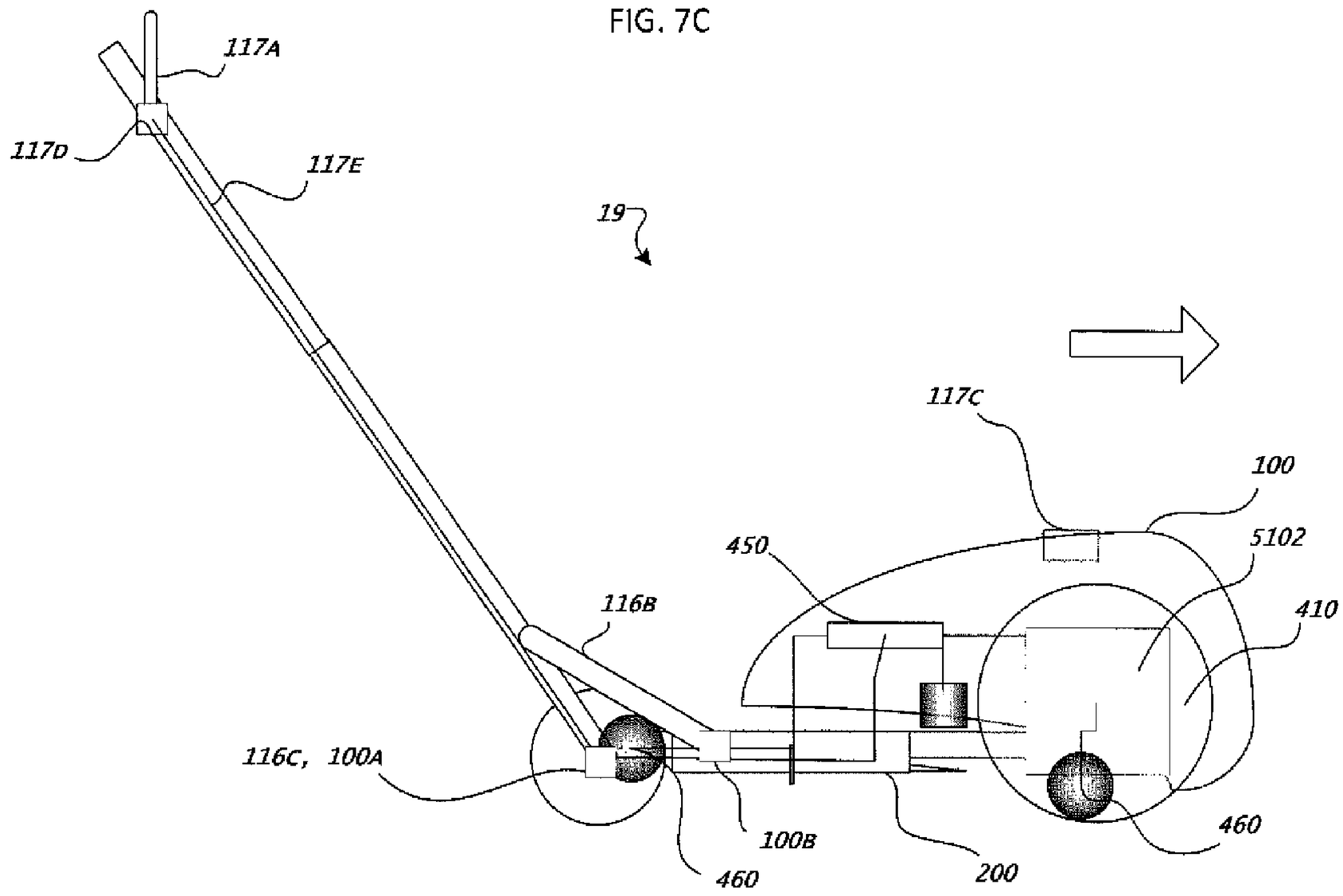

117A
117D
117E
19
117C
100
450
5102
410
116B
116C, 100A
100B
460
200
460

FIG. 7D

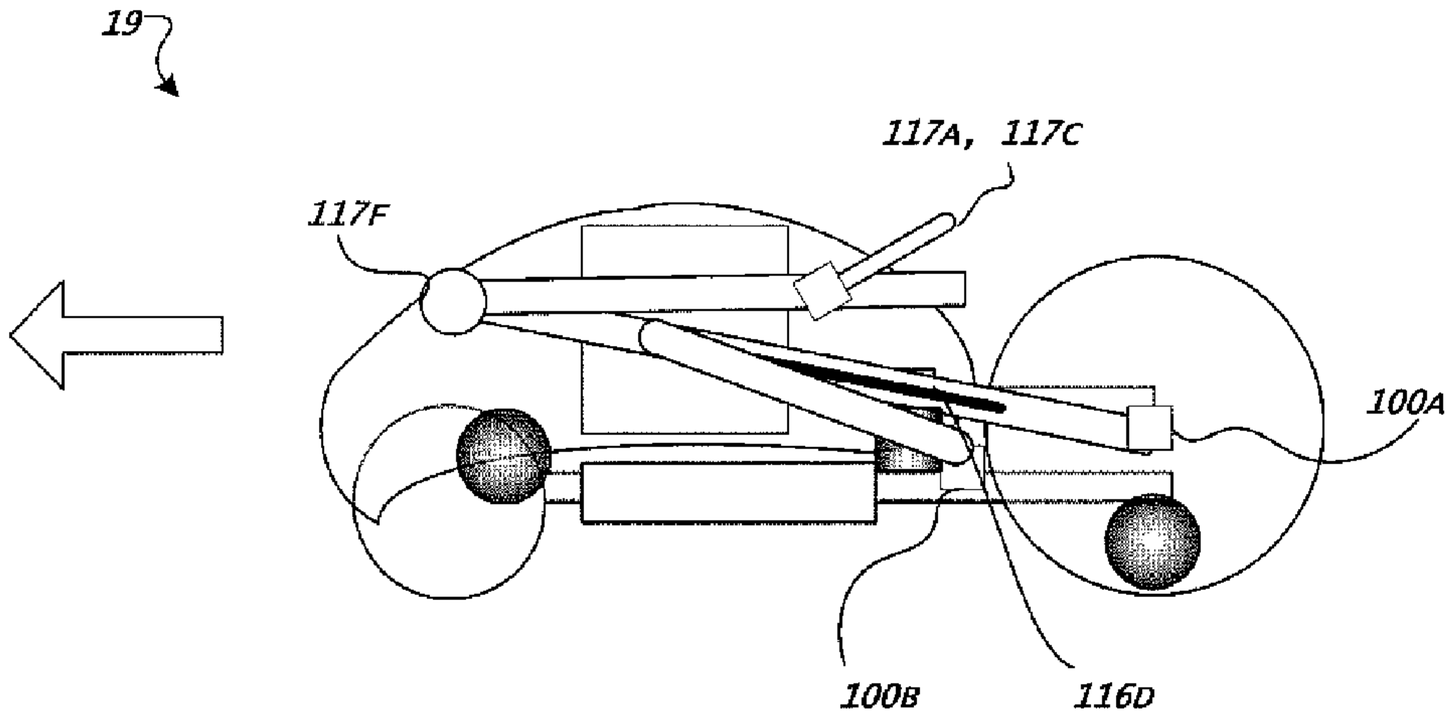

19
117A, 117C
117F
100A
100B
116D

FIG. 7E

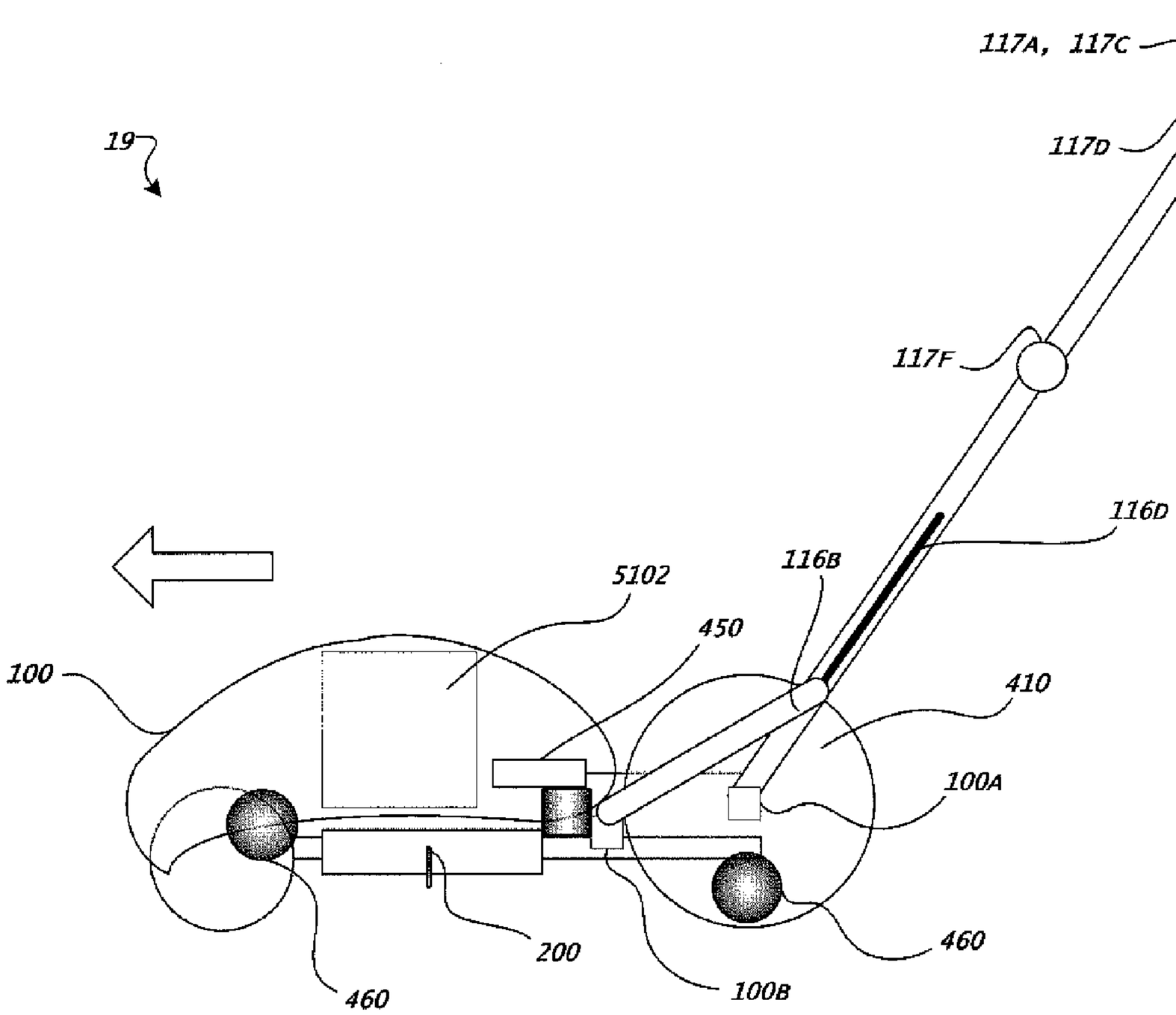

19
117A, 117C
117D
117F
116D
116B
5102
450
100
410
100A
460
200
100B
460

FIG. 7F

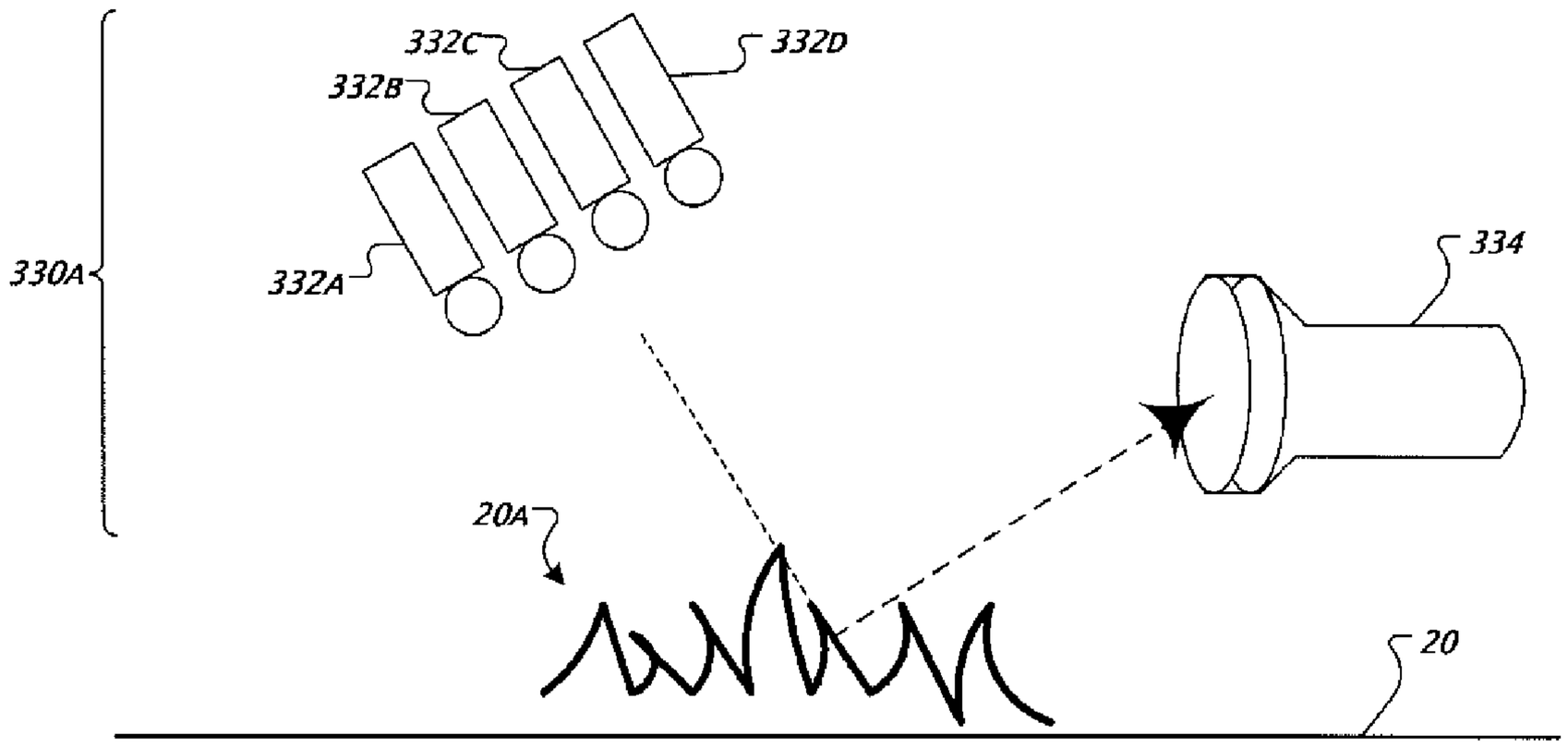


FIG. 8A

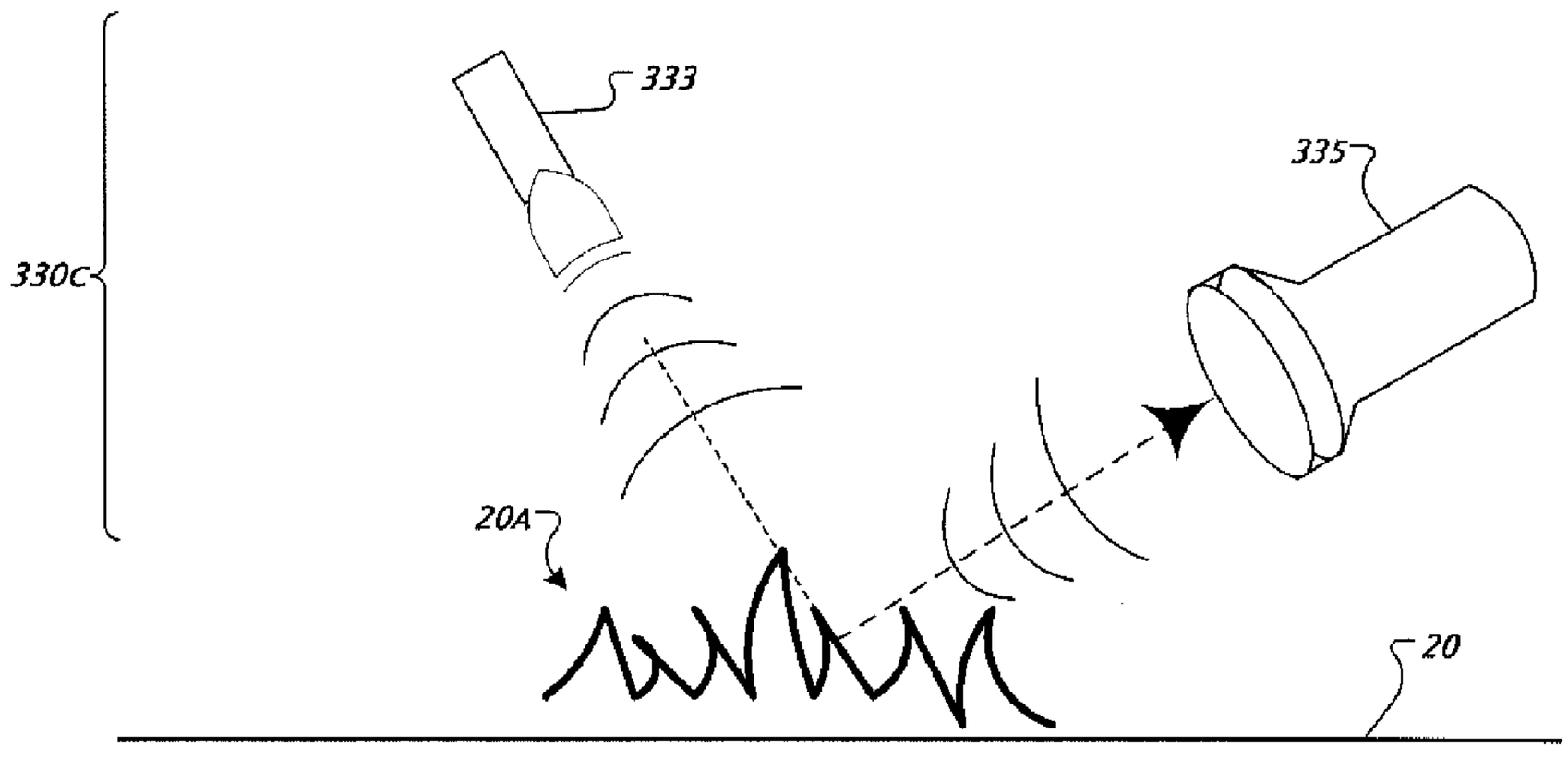


FIG. 8C

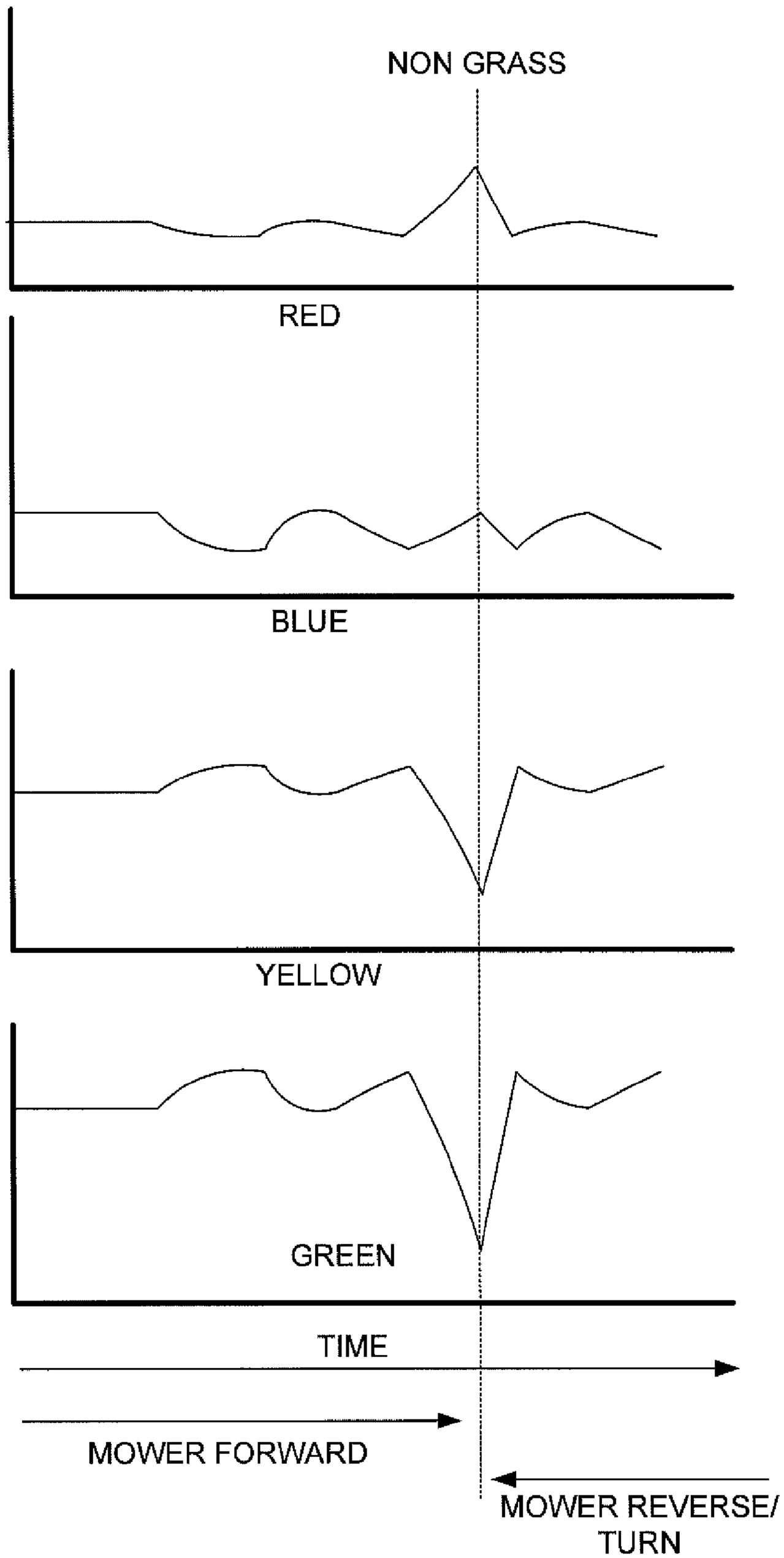

NON GRASS
RED
BLUE
YELLOW
GREEN
TIME
MOWER FORWARD
MOWER REVERSE/
TURN

FIG. 8B

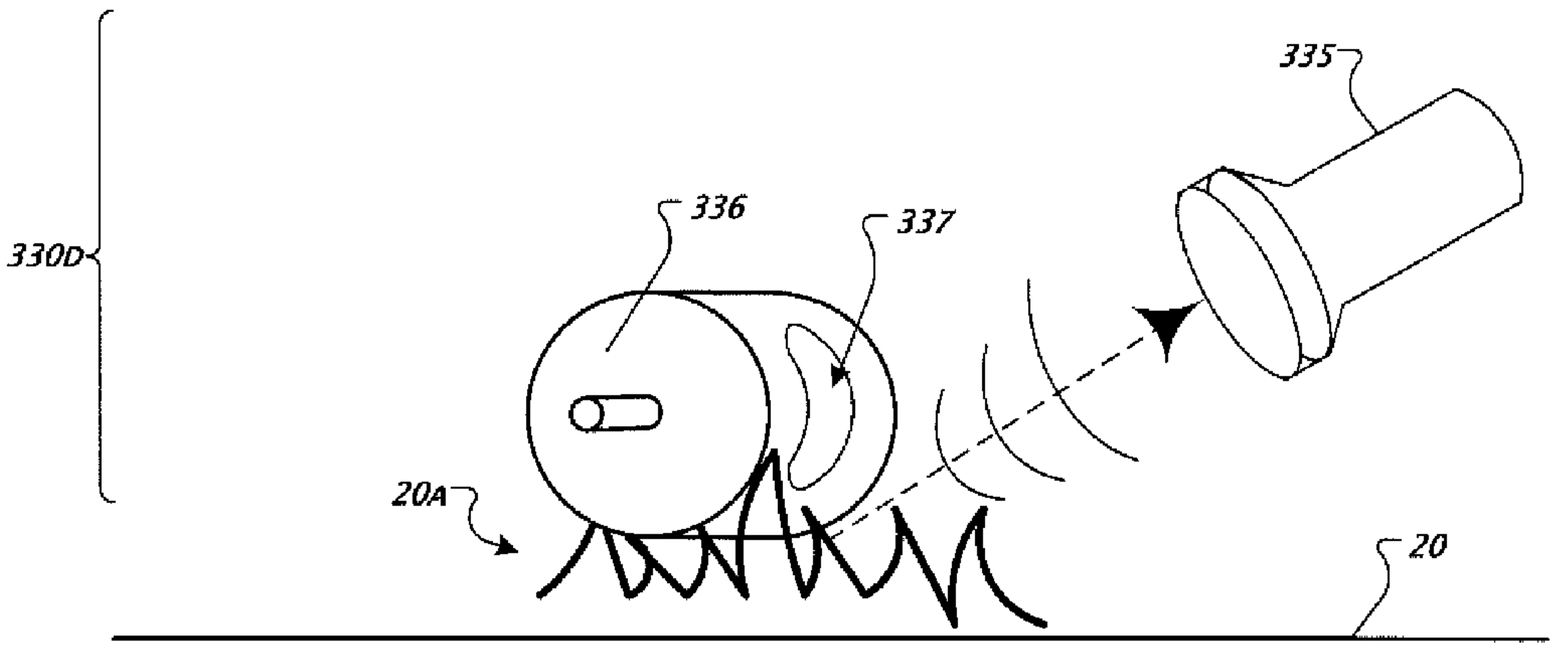

330D
335
336
337
20A
20

FIG. 8D

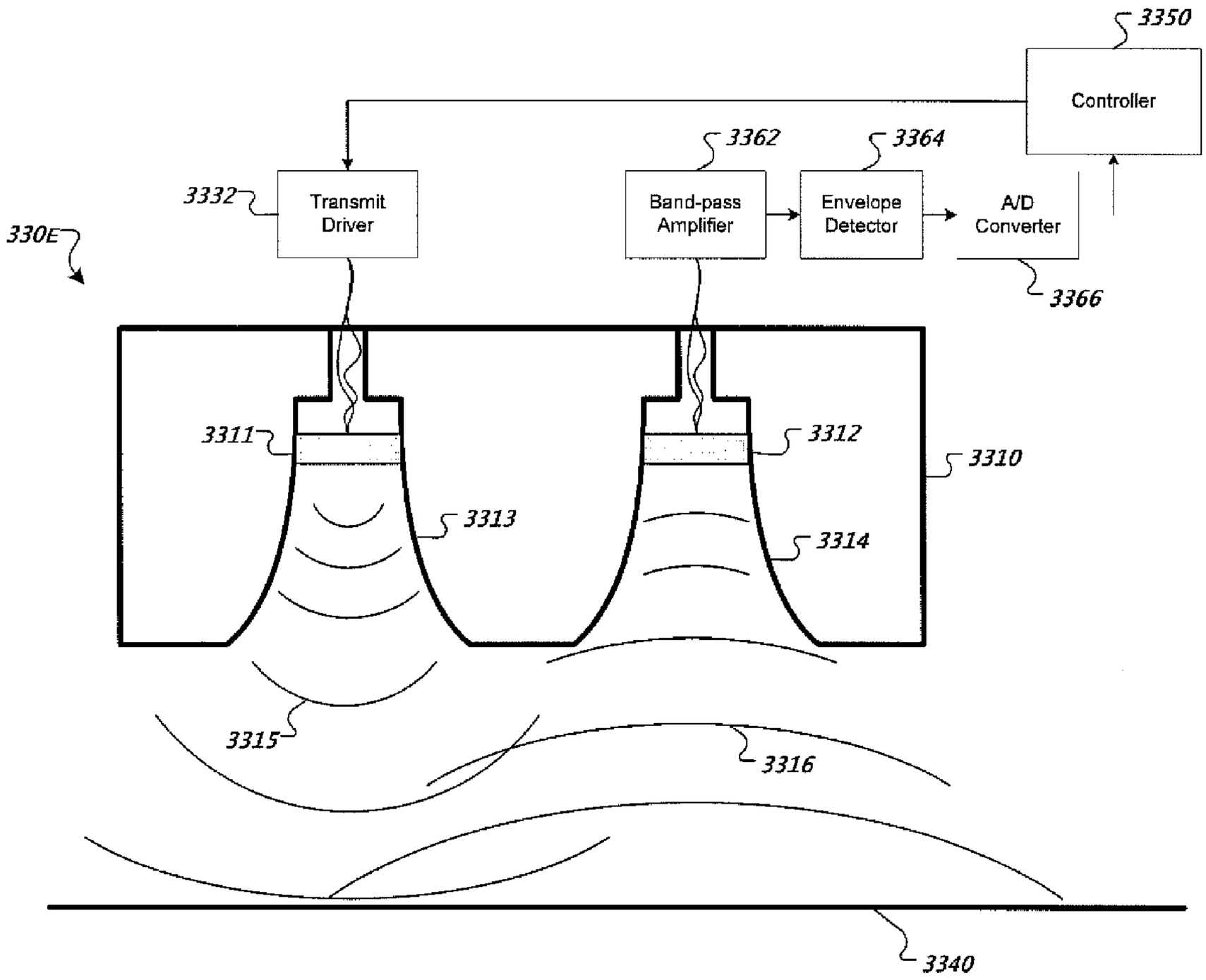

330E
3350
Controller
3332
Transmit Driver
3362
Band-pass Amplifier
3364
Envelope Detector
A/D Converter
3366
3311
3312
3310
3313
3314
3315
3316
3340

FIG. 8E

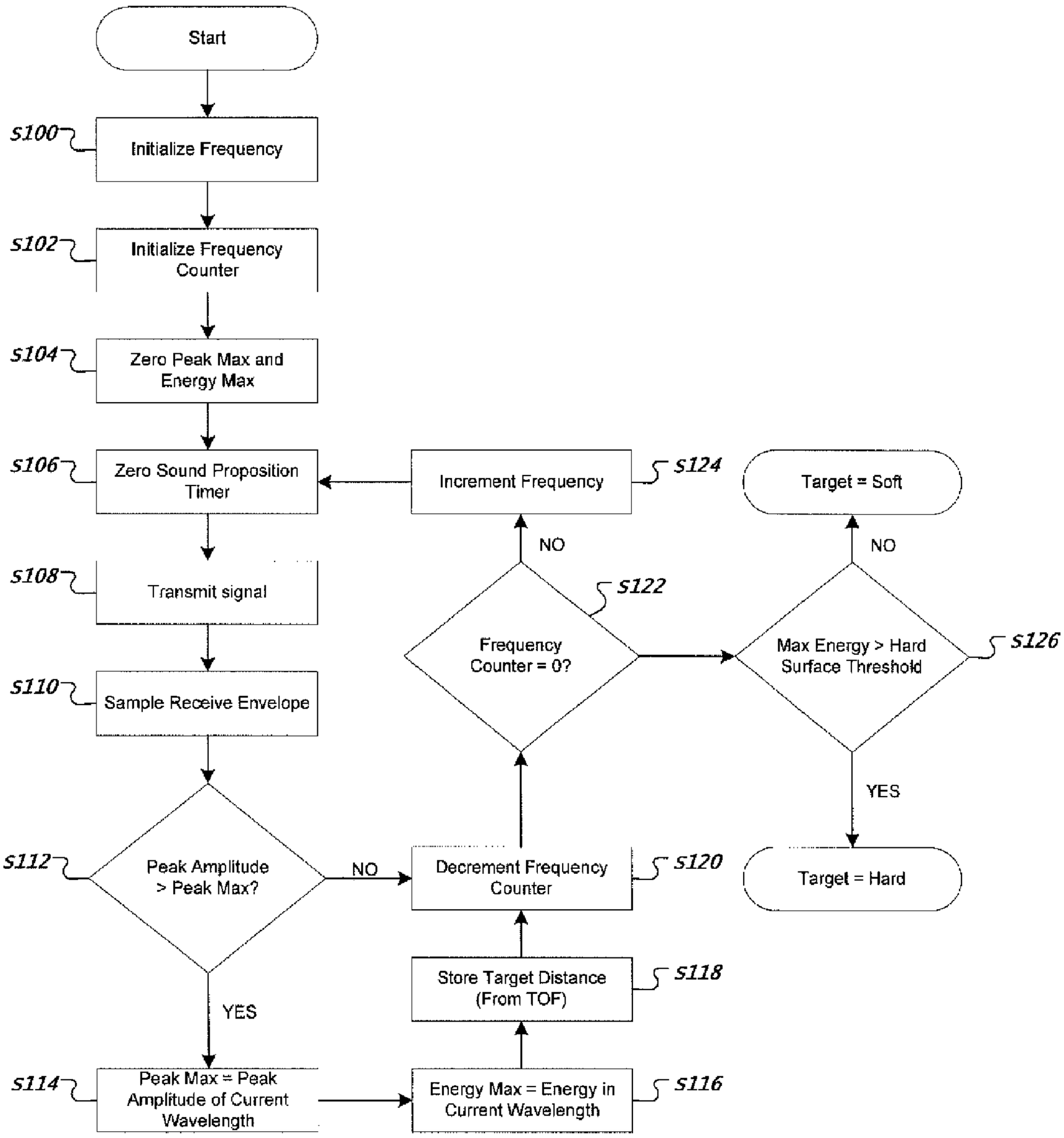

Start
S100
Initialize Frequency
S102
Initialize Frequency Counter
S104
Zero Peak Max and Energy Max
S106
Zero Sound Proposition Timer
S108
Transmit signal
S110
Sample Receive Envelope
S112
Peak Amplitude > Peak Max?
NO
YES
S114
Peak Max = Peak Amplitude of Current Wavelength
S116
Energy Max = Energy in Current Wavelength
S118
Store Target Distance (From TOF)
S120
Decrement Frequency Counter
S122
Frequency Counter = 0?
NO
S124
Increment Frequency
S126
Max Energy > Hard Surface Threshold
NO
Target = Soft
YES
Target = Hard

FIG. 8F

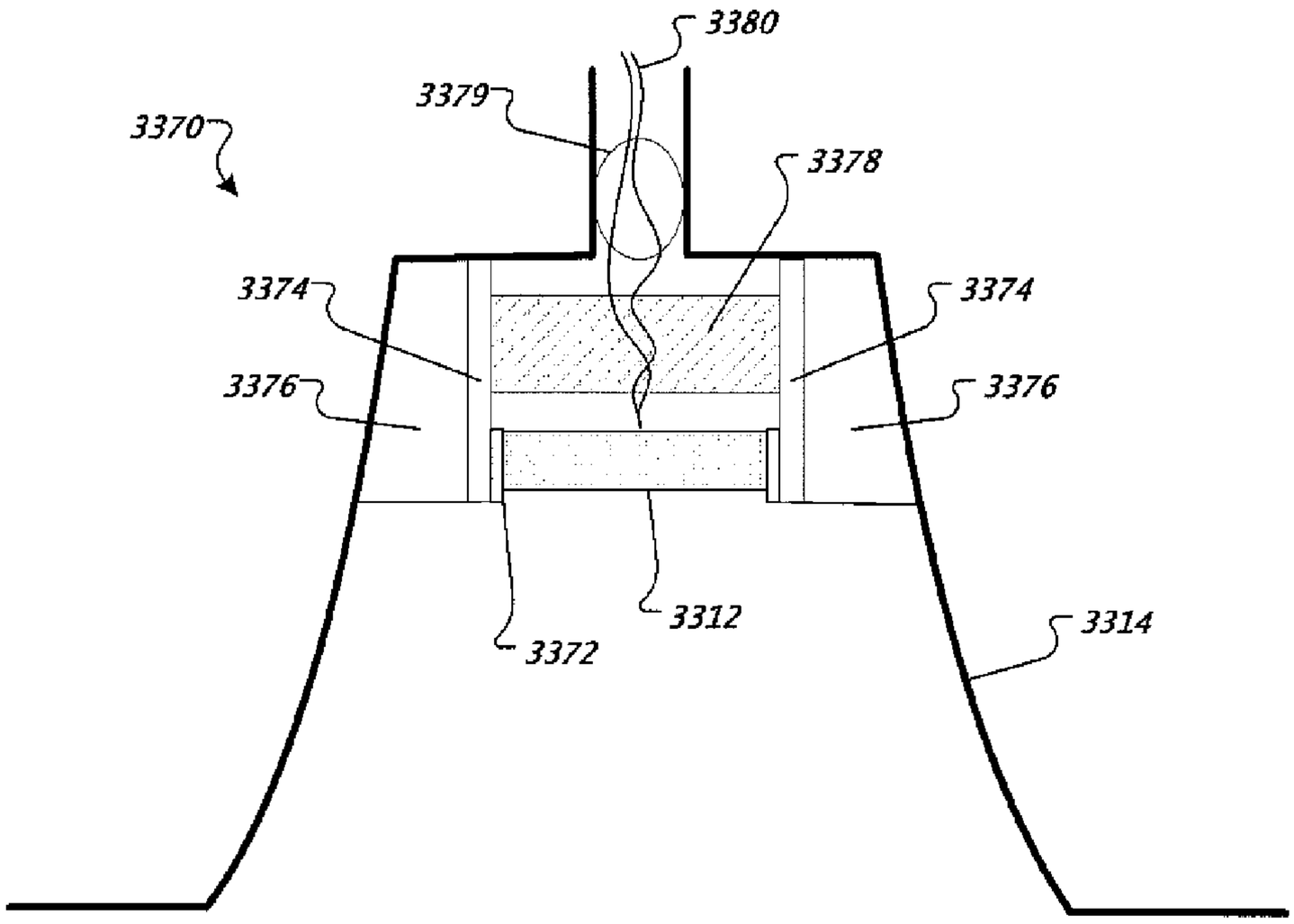

3380
3379
3370
3378
3374
3374
3376
3376
3372
3312
3314

FIG. 8G

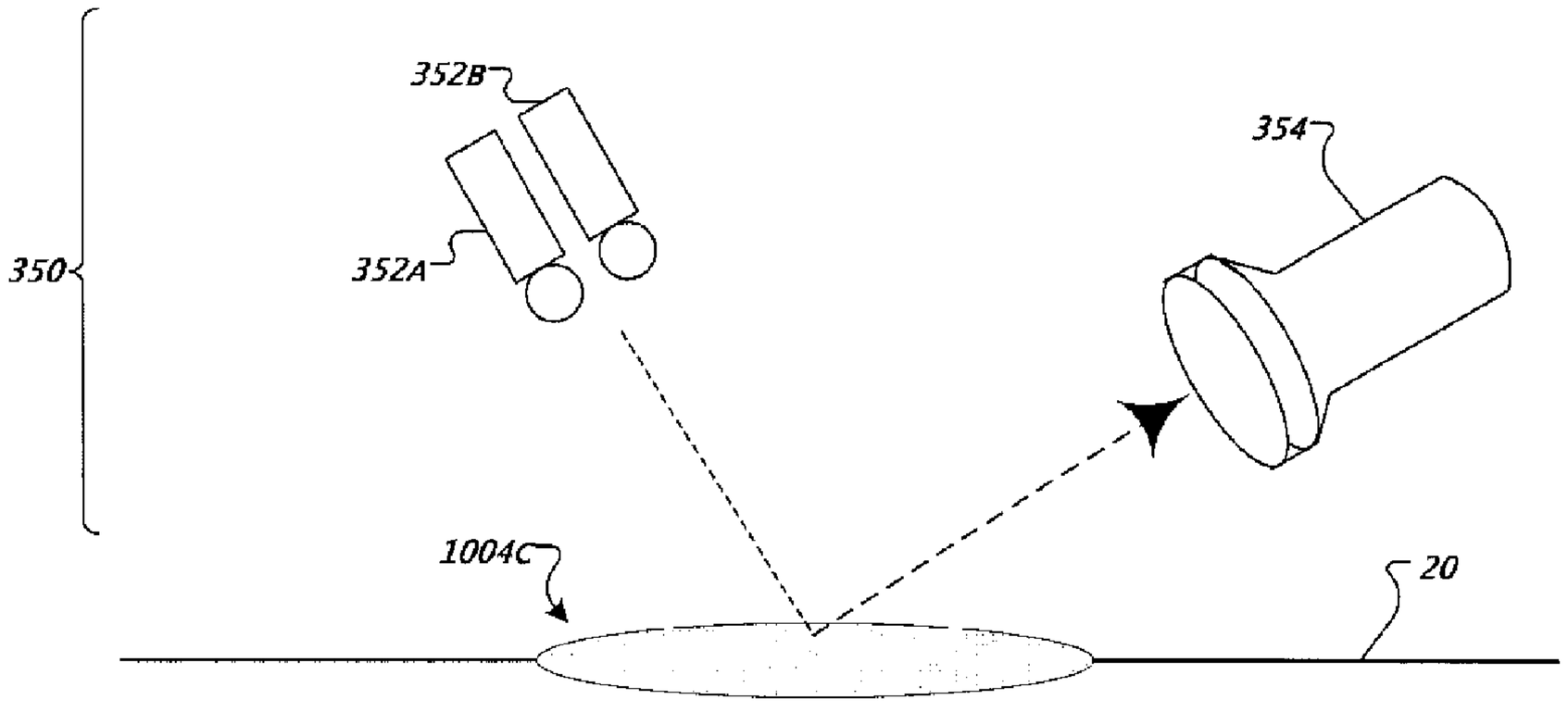

352B
354
350
352A
1004C
20

FIG. 9

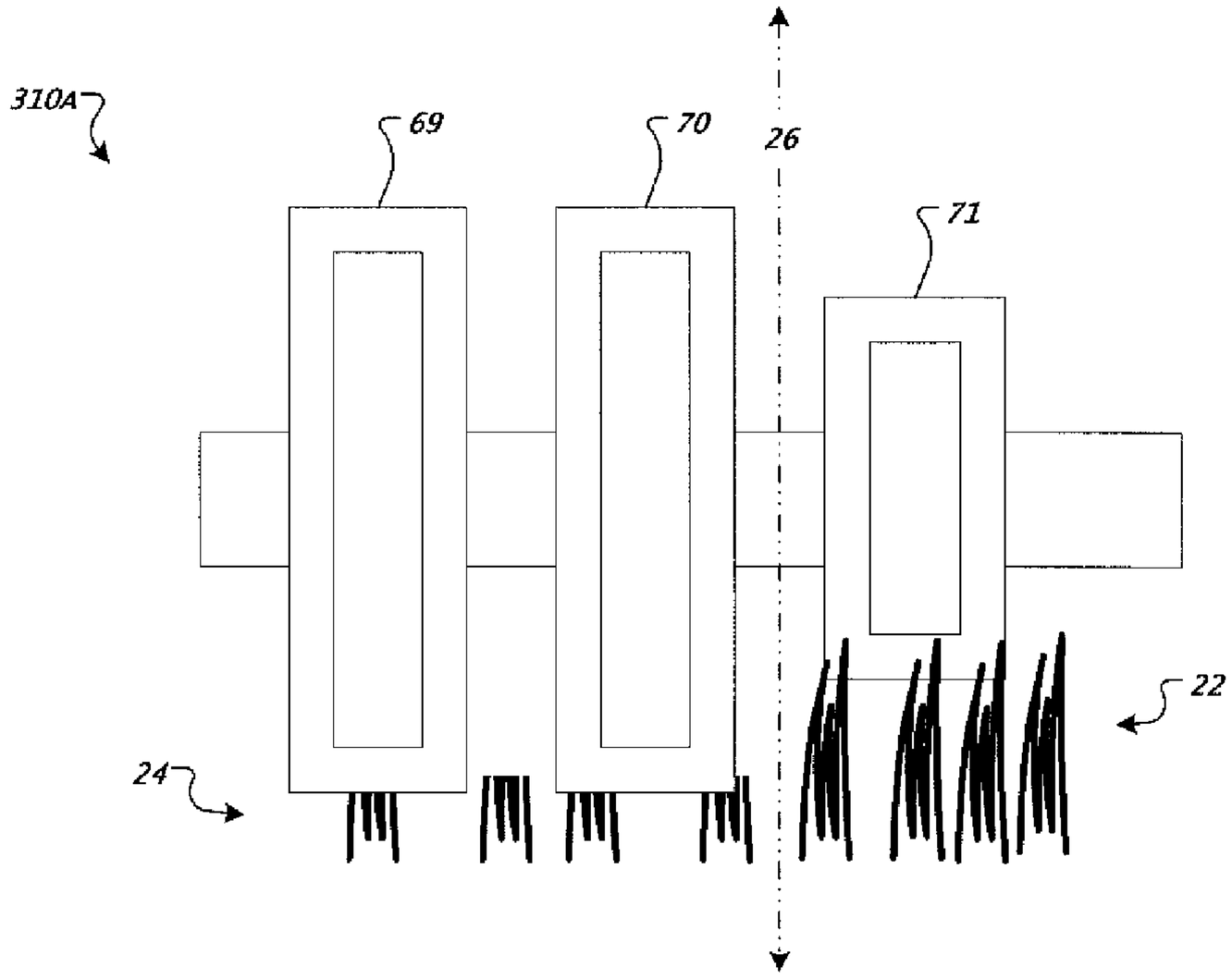


FIG. 10

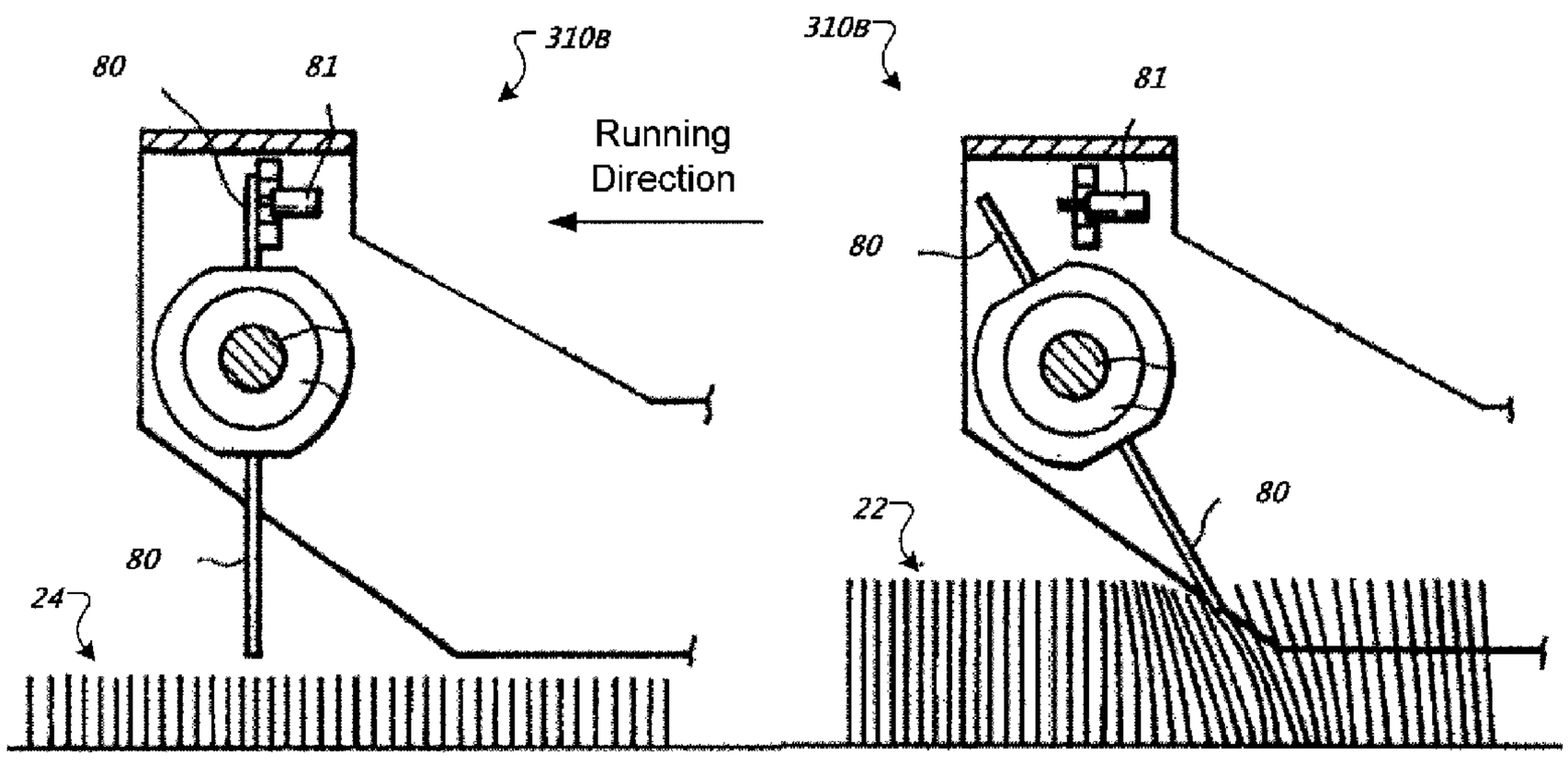


FIG. 11A

FIG. 11B

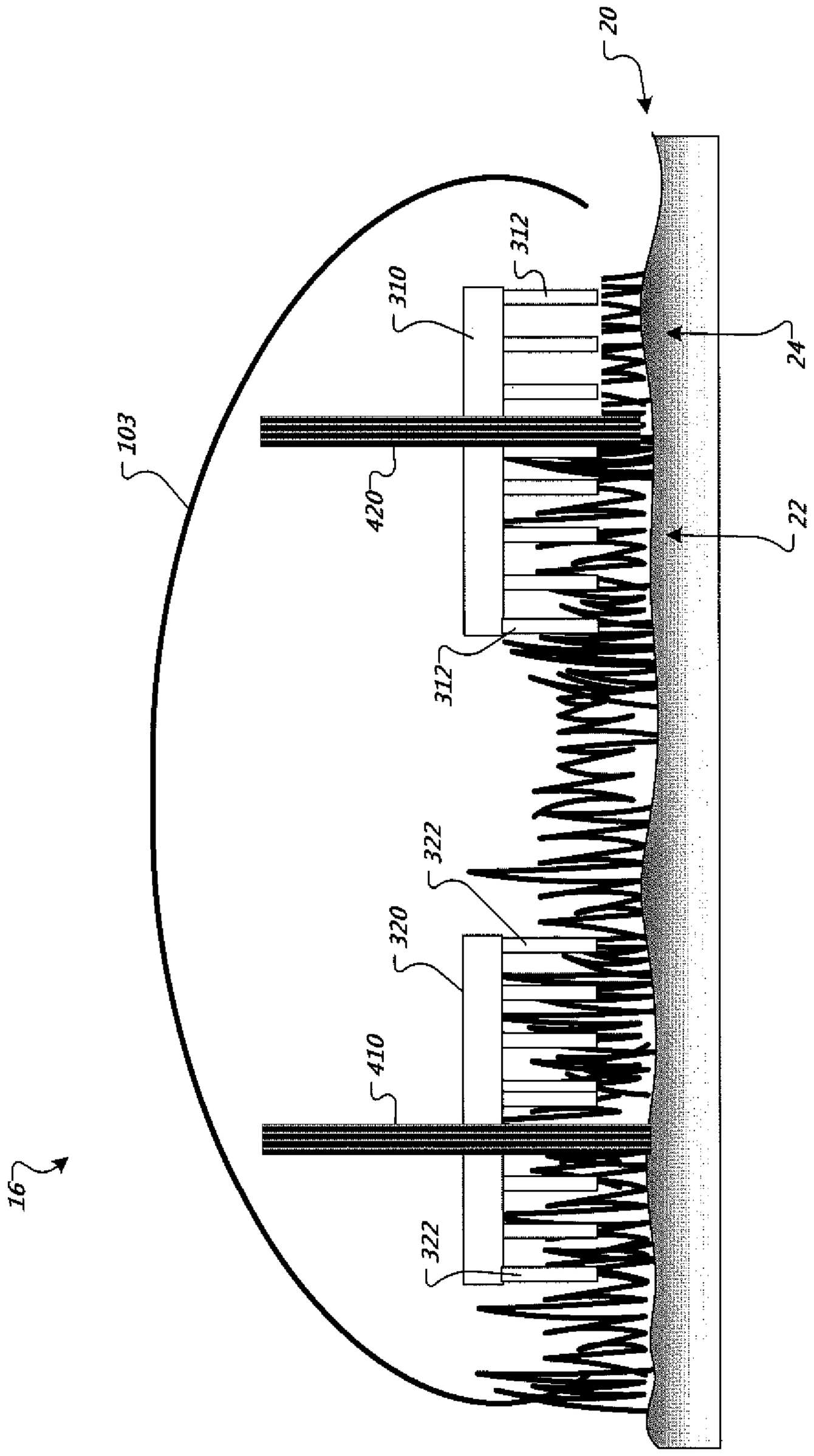


FIG. 12

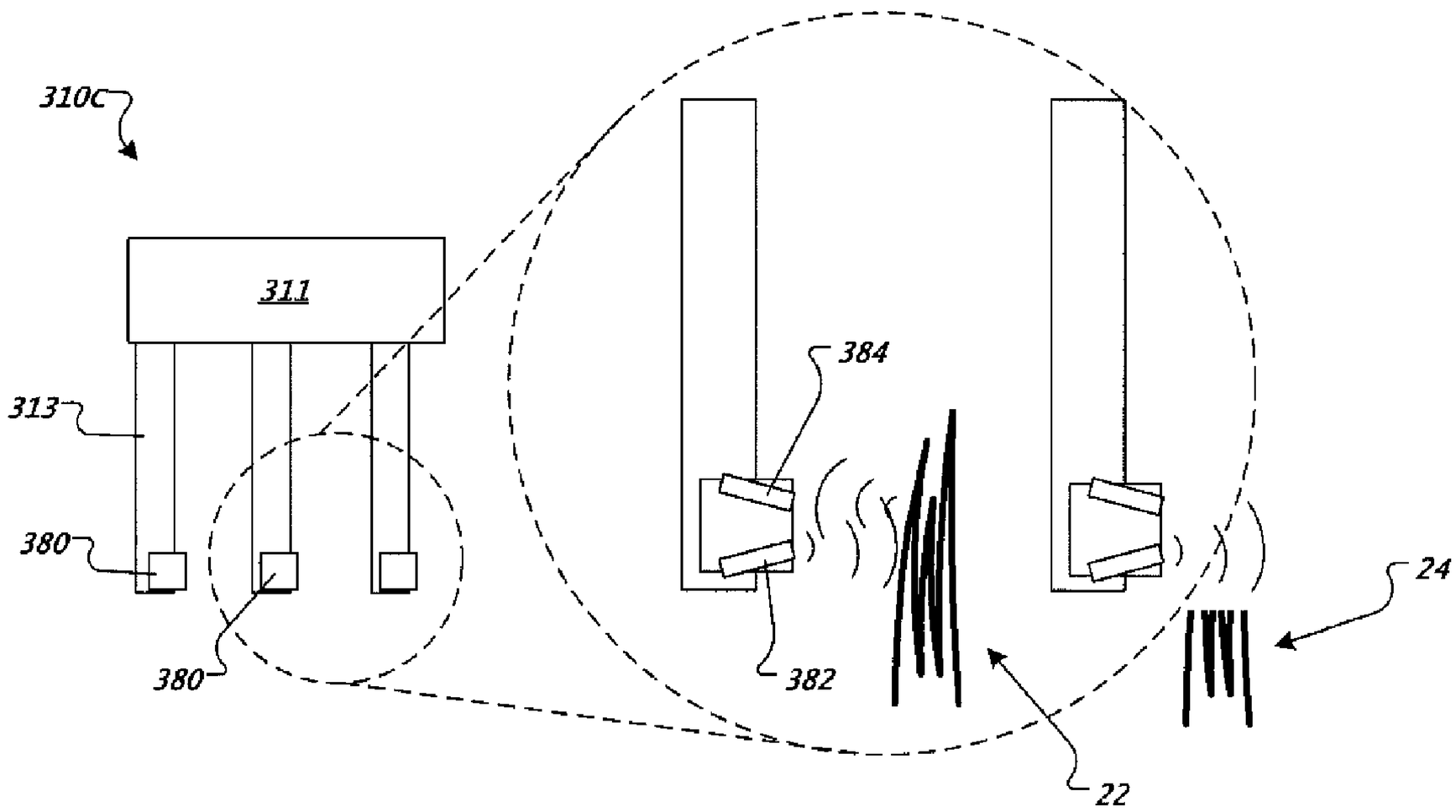


FIG. 13

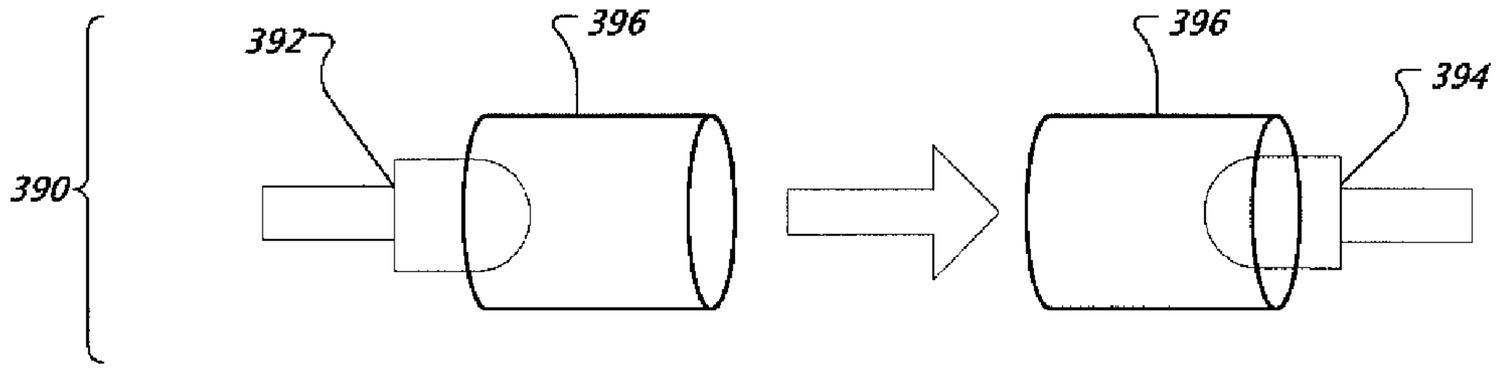


FIG. 14

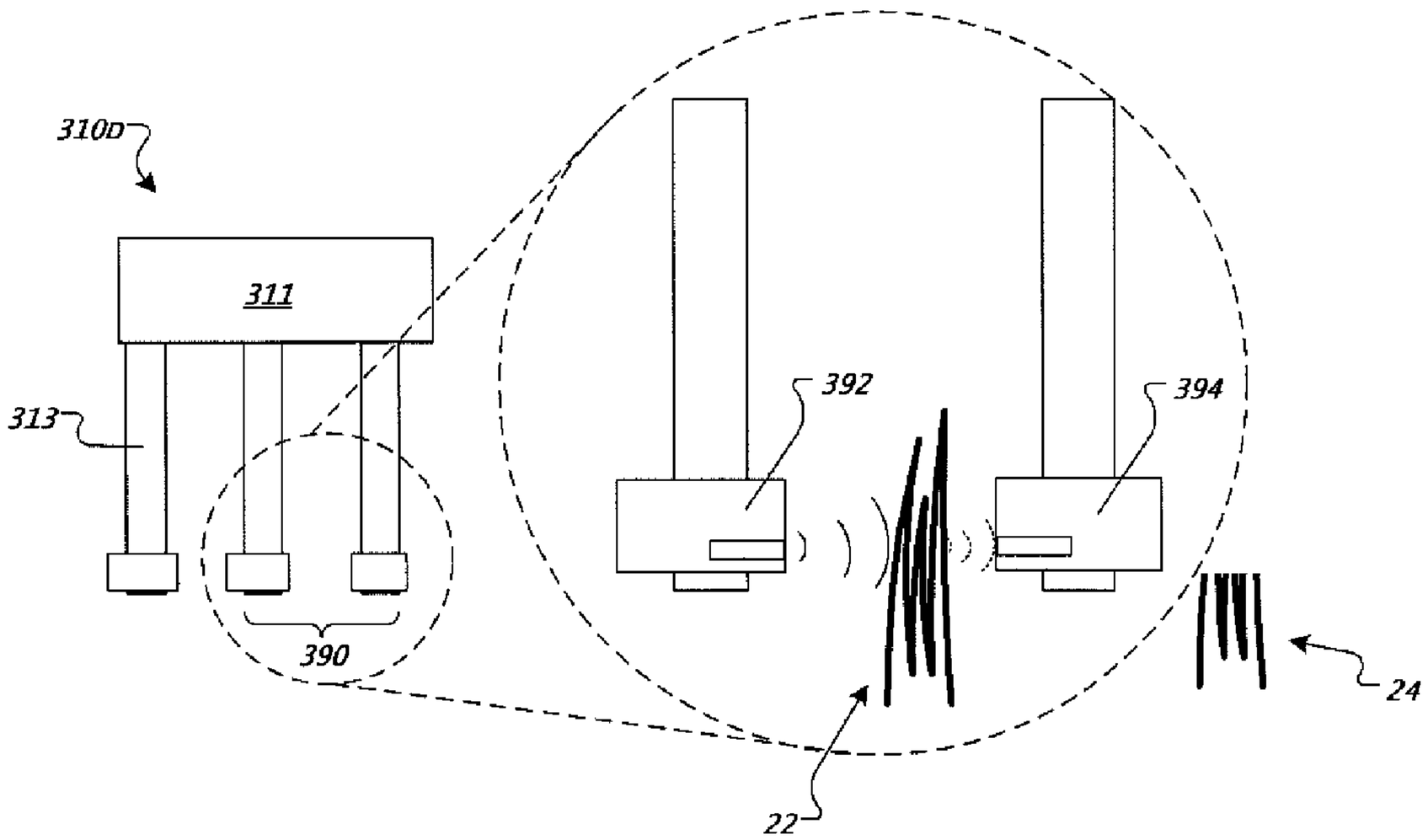


FIG. 15A

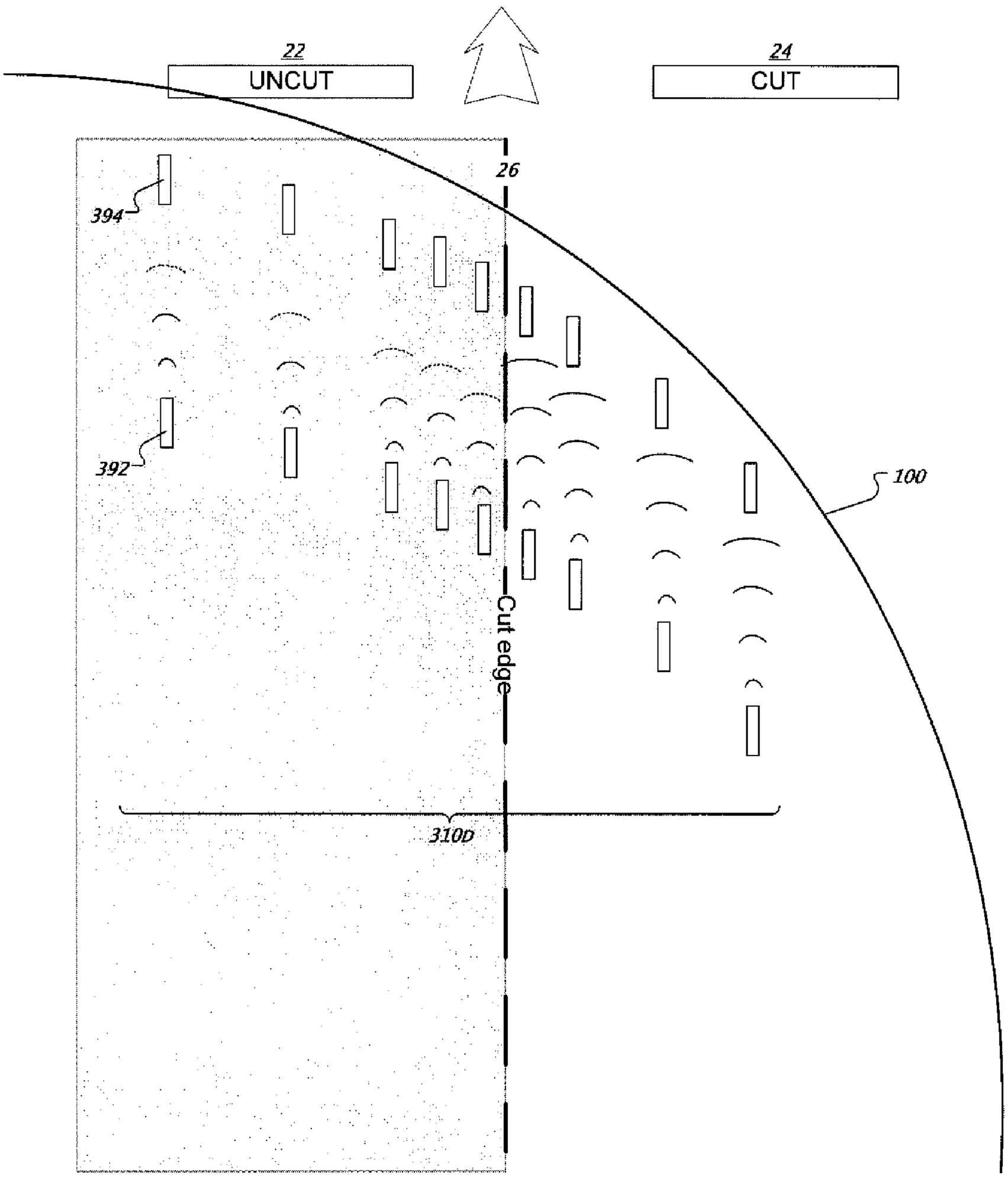


FIG. 15B

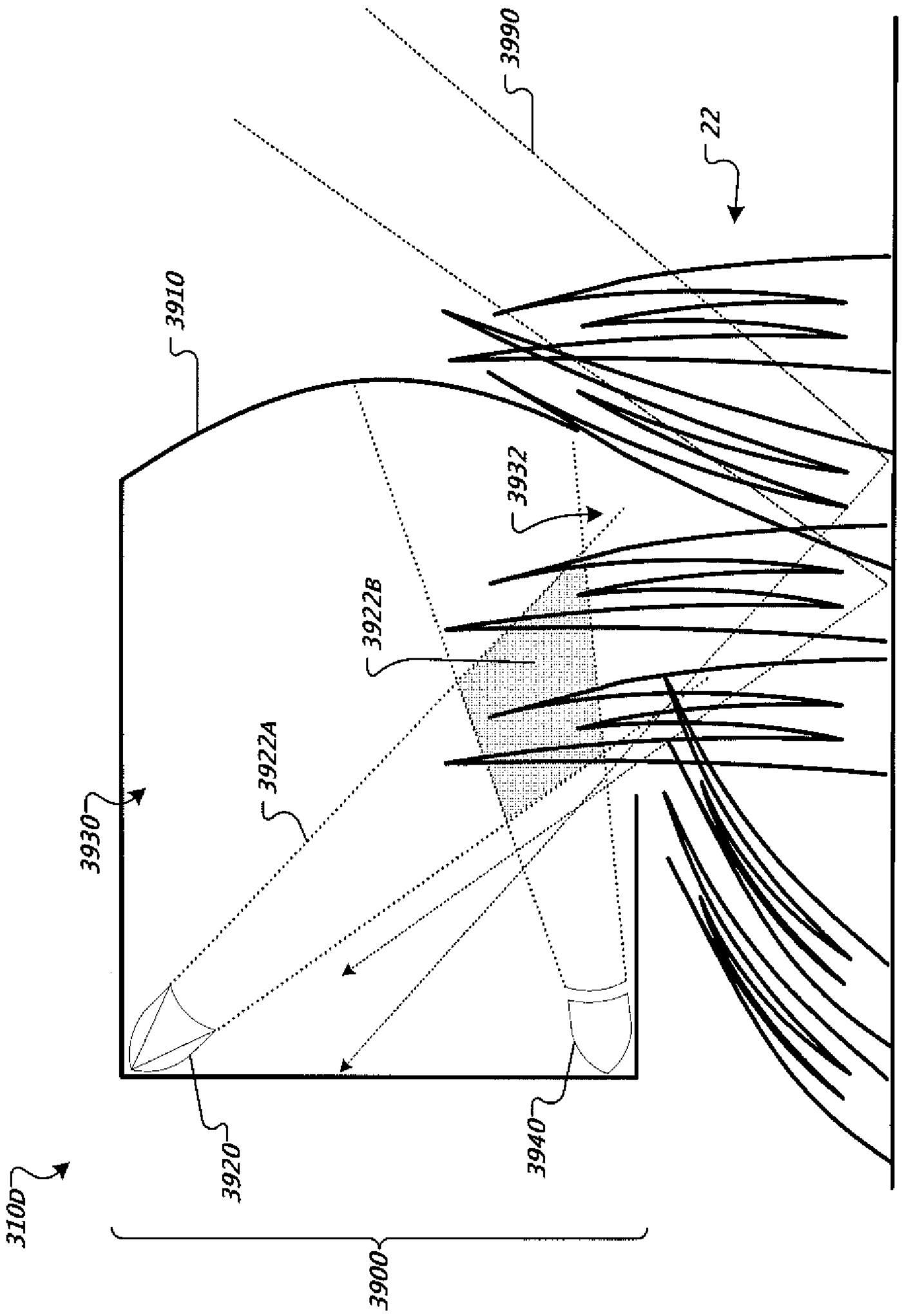


FIG. 16A

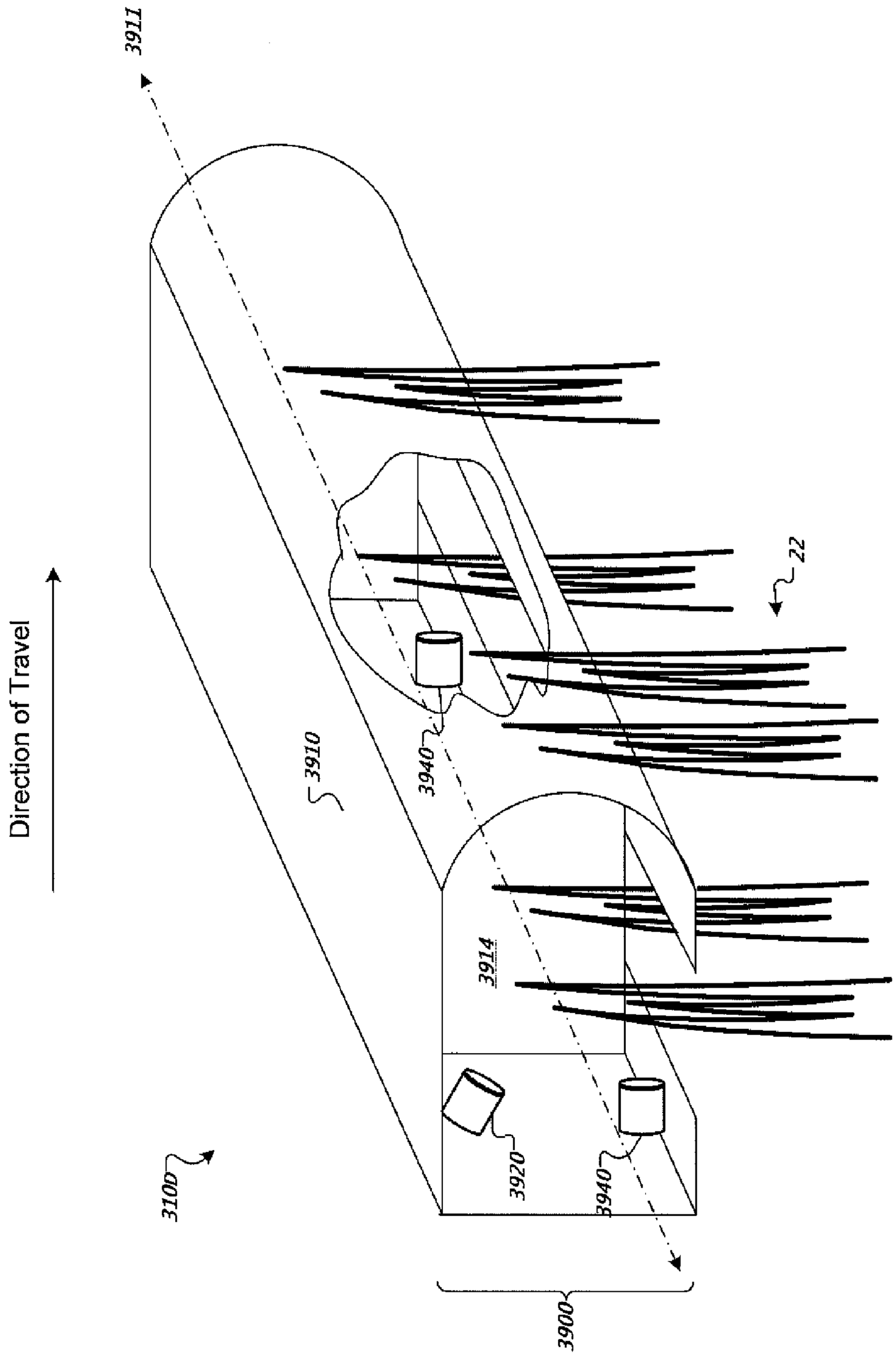

3911
Direction of Travel
3910
3940
22
3914
3920
3940
310D
3900

FIG. 16B

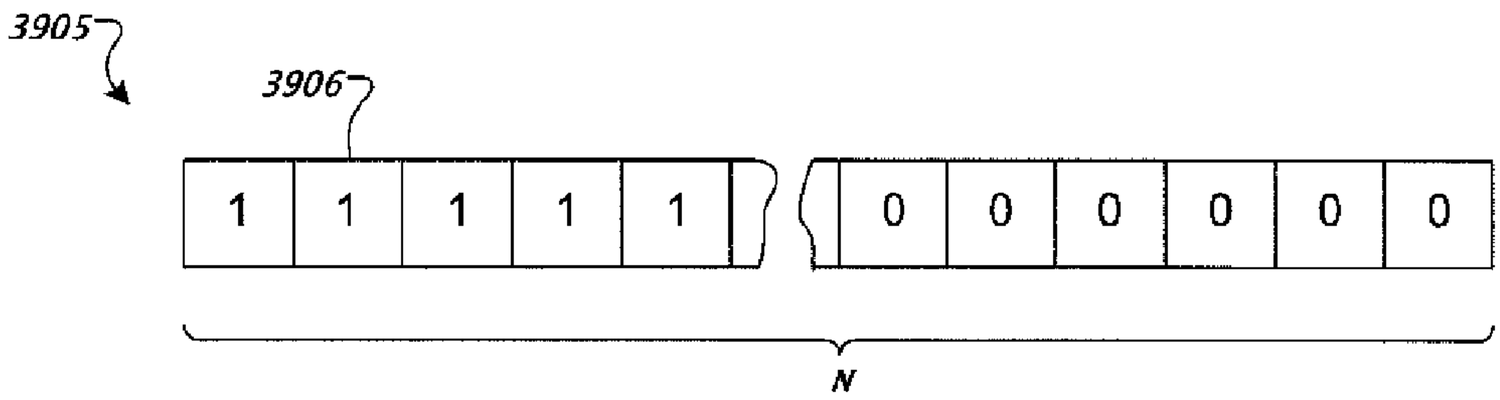


FIG. 16C

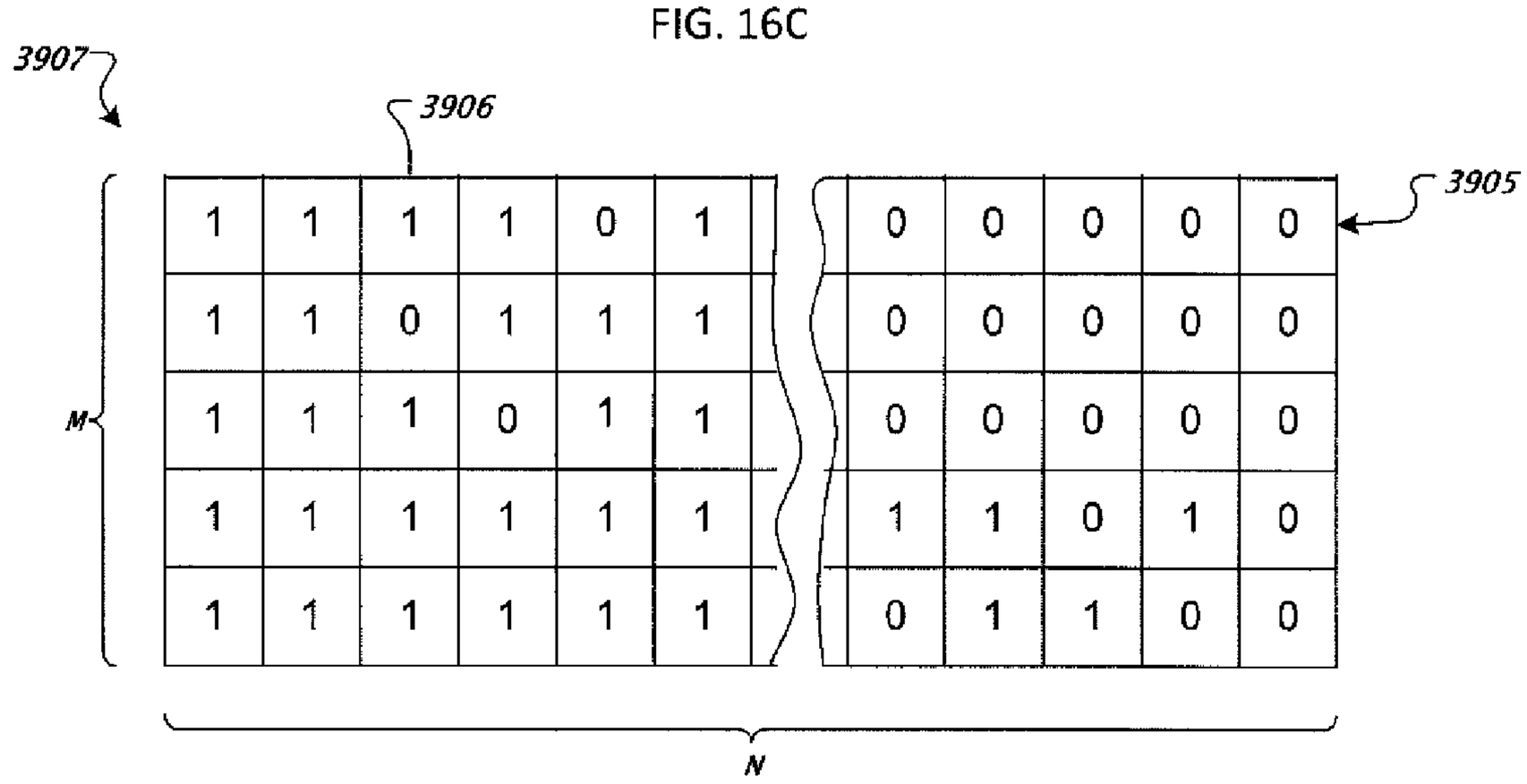


FIG. 16D

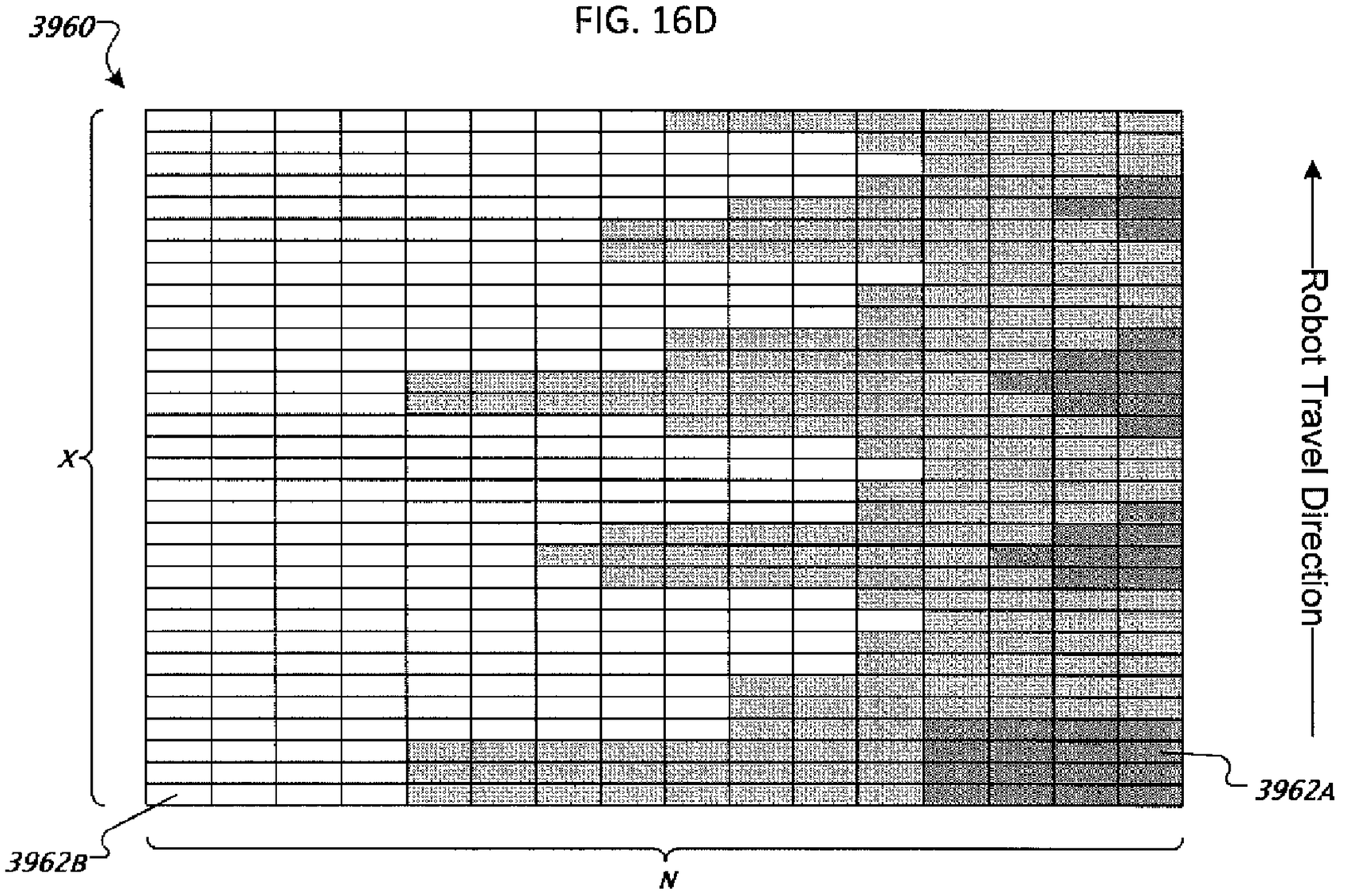


FIG. 16E

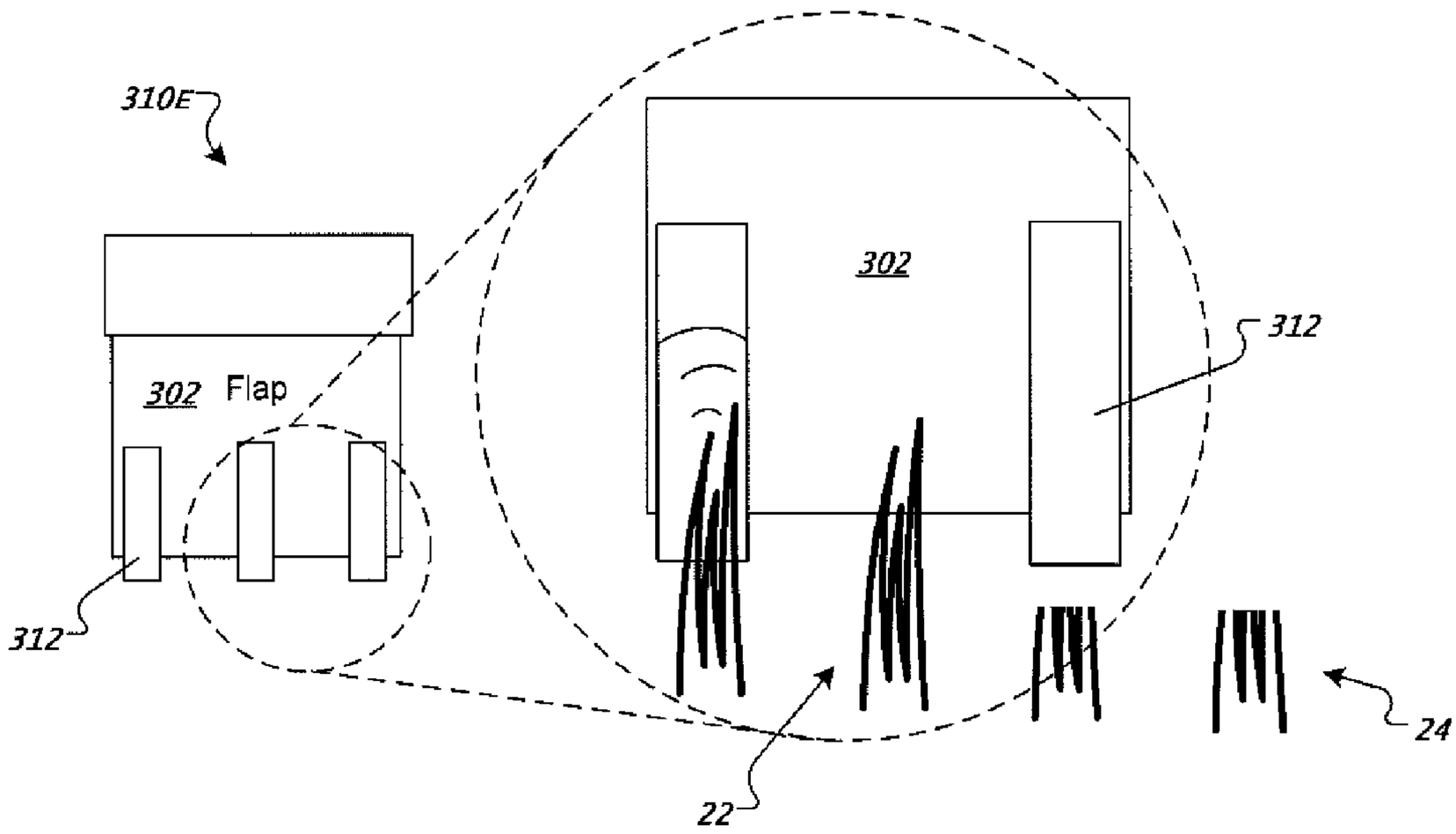

310E
302
Flap
312
302
312
22
24

FIG. 17

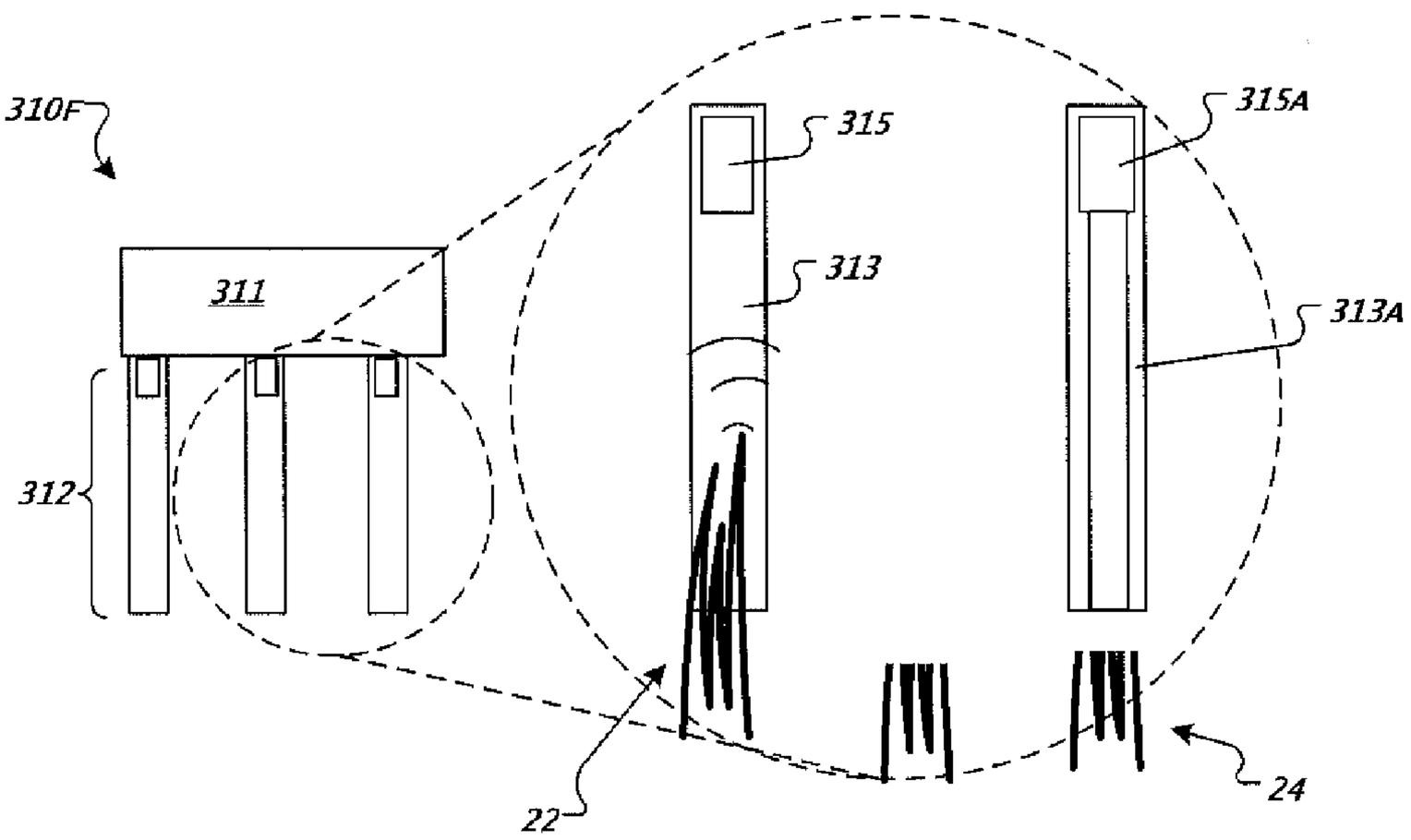

310F
311
312
315
313
315A
313A
22
24

FIG. 18

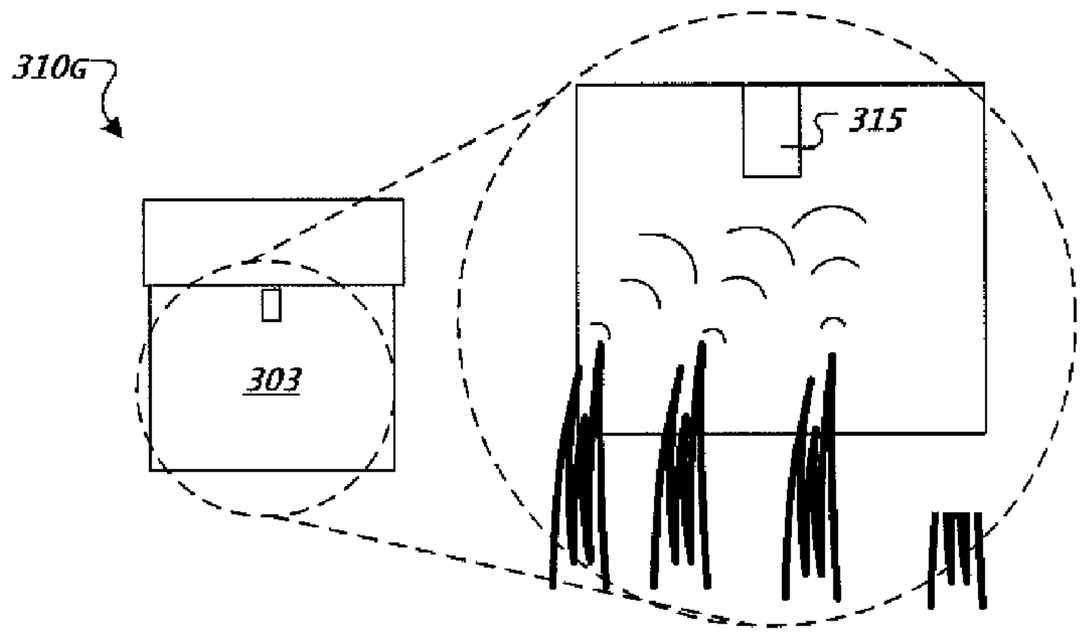


FIG. 19

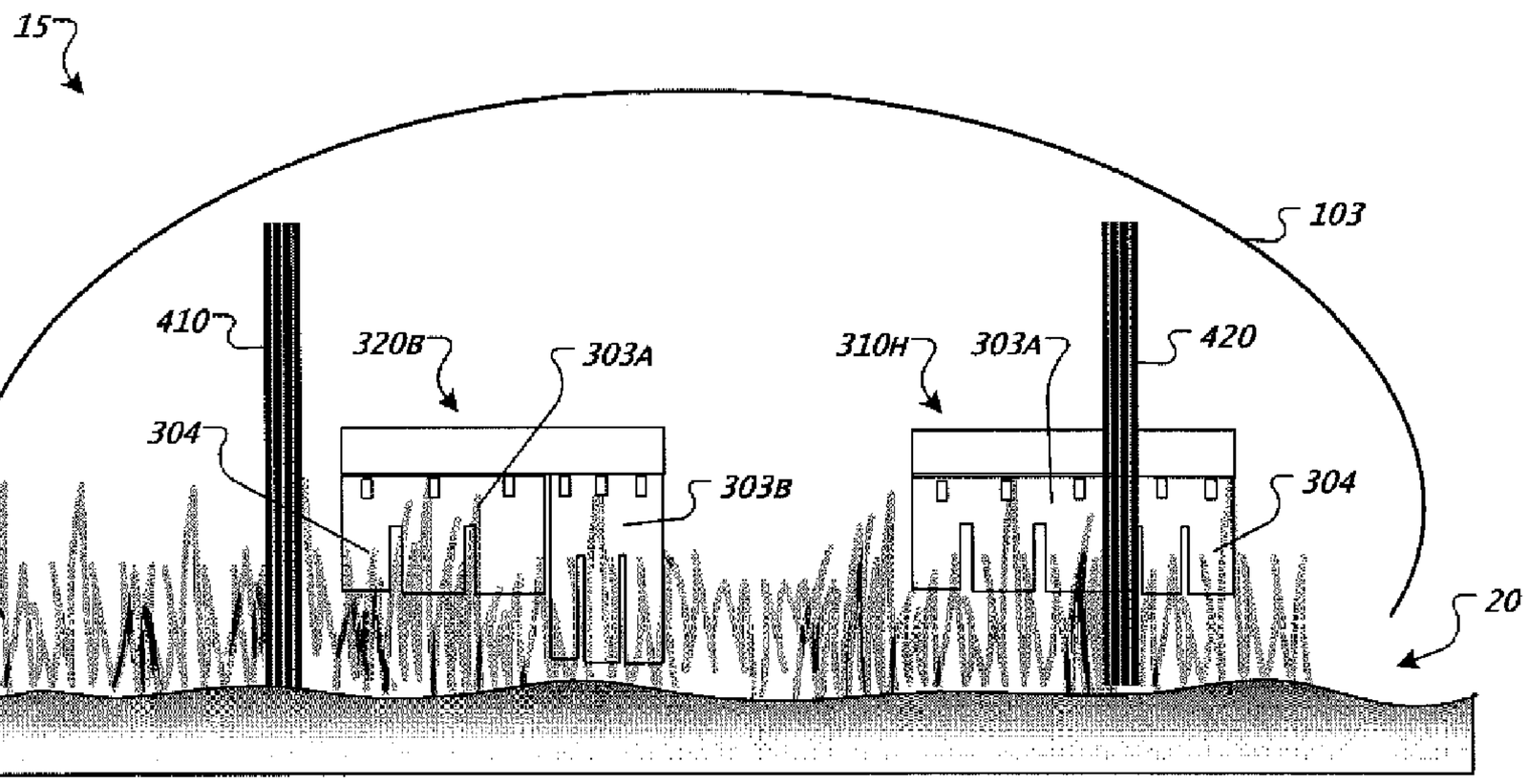


FIG. 20

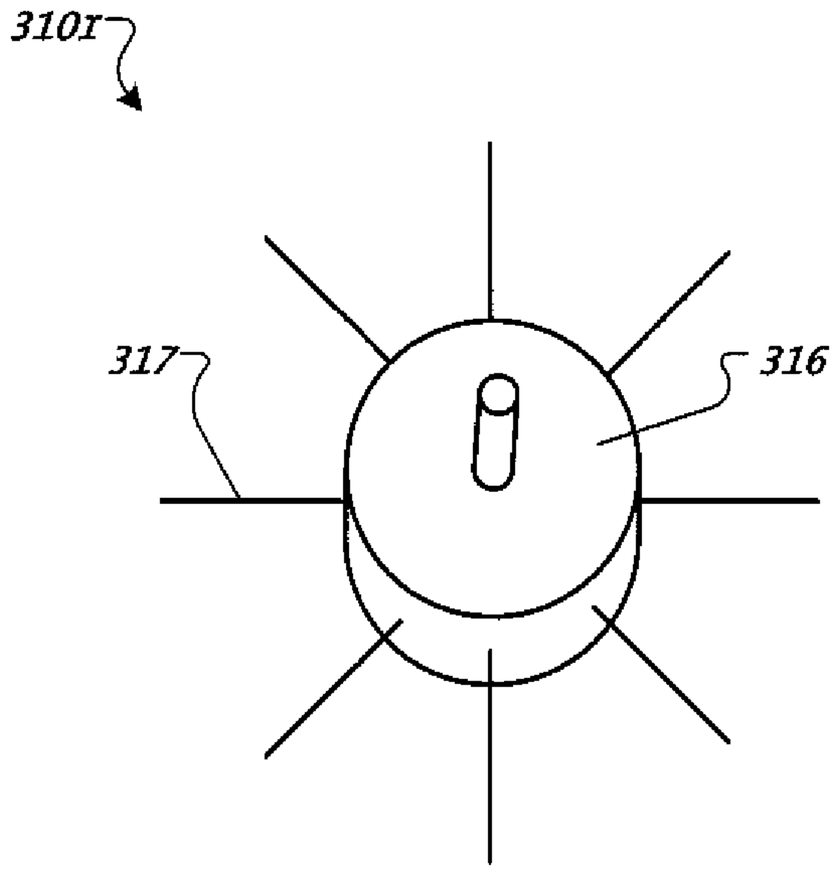


FIG. 21

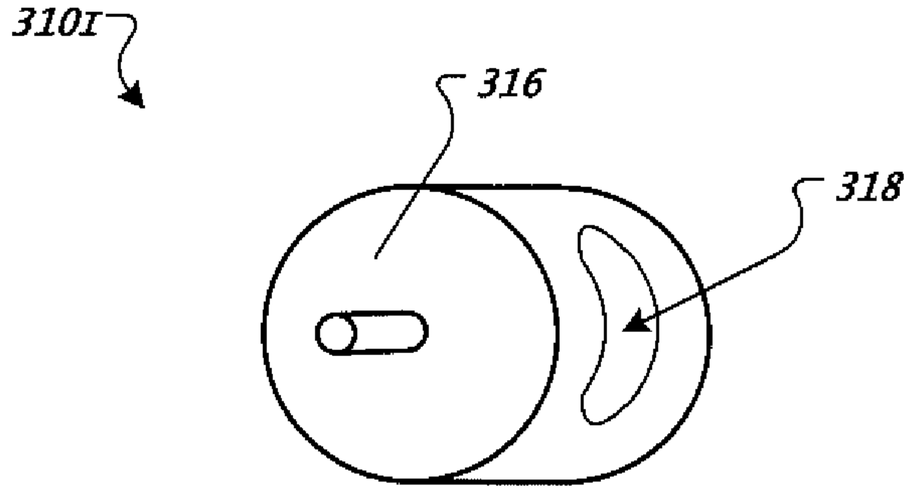


FIG. 22

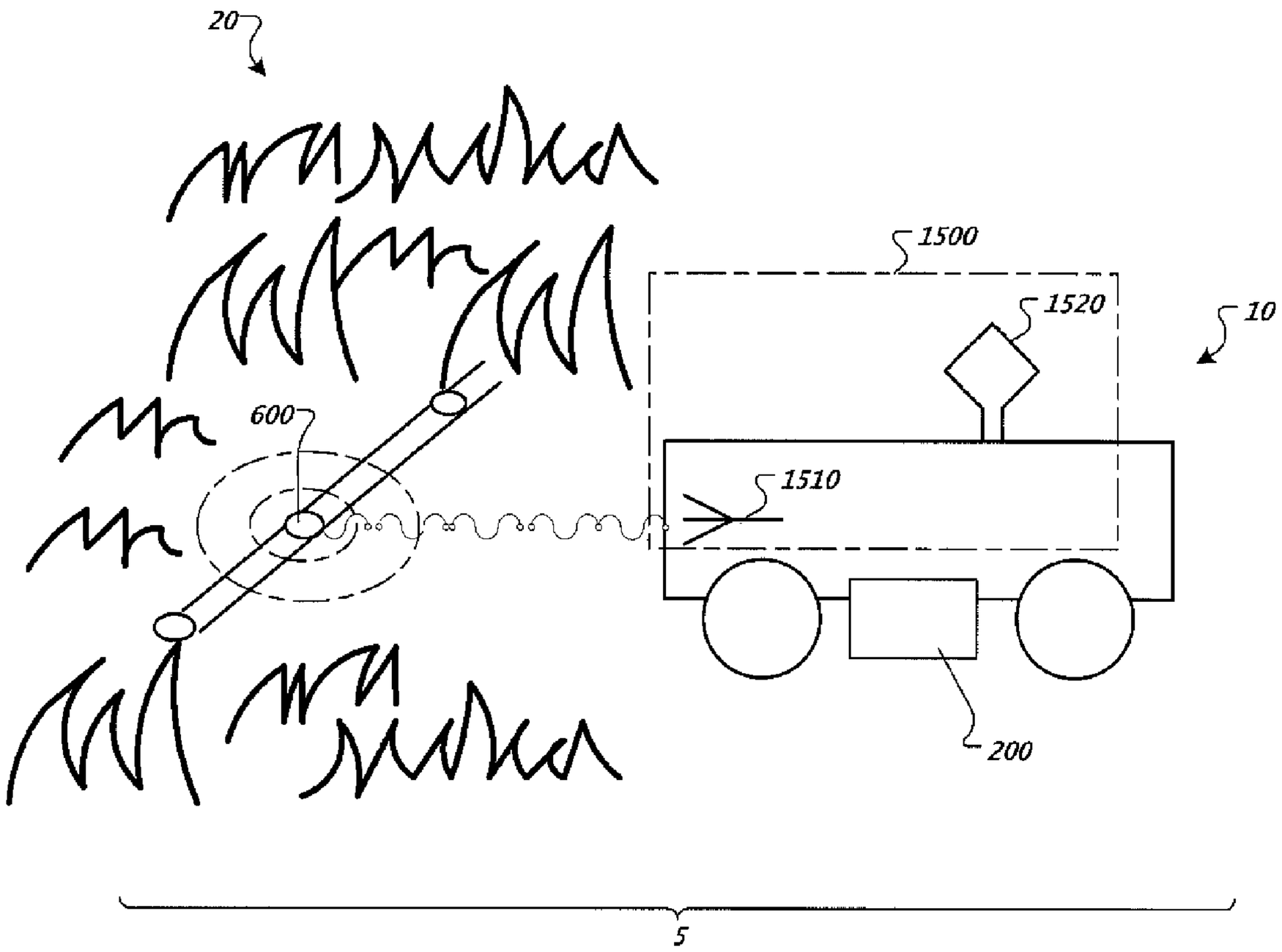


FIG. 23A

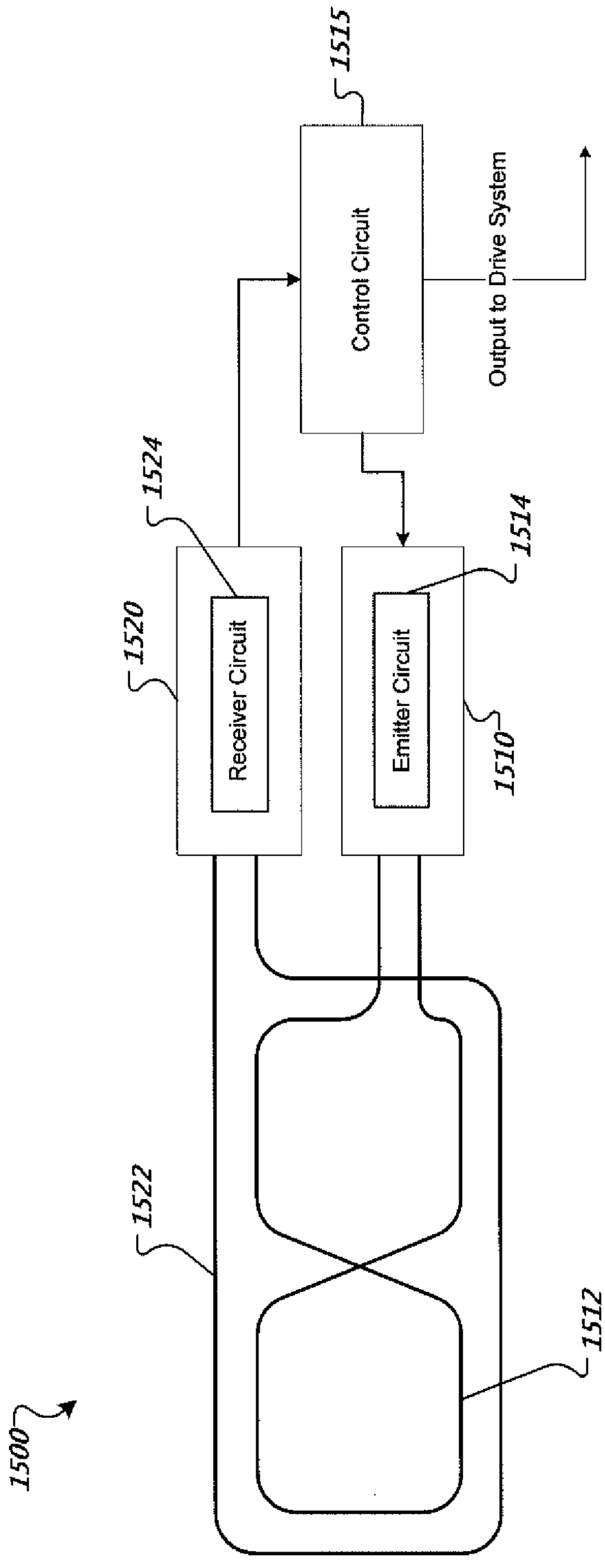

1500
1512
1522
1510
1514
1520
1524
1515
Receiver Circuit
Emitter Circuit
Control Circuit
Output to Drive System

FIG. 23B

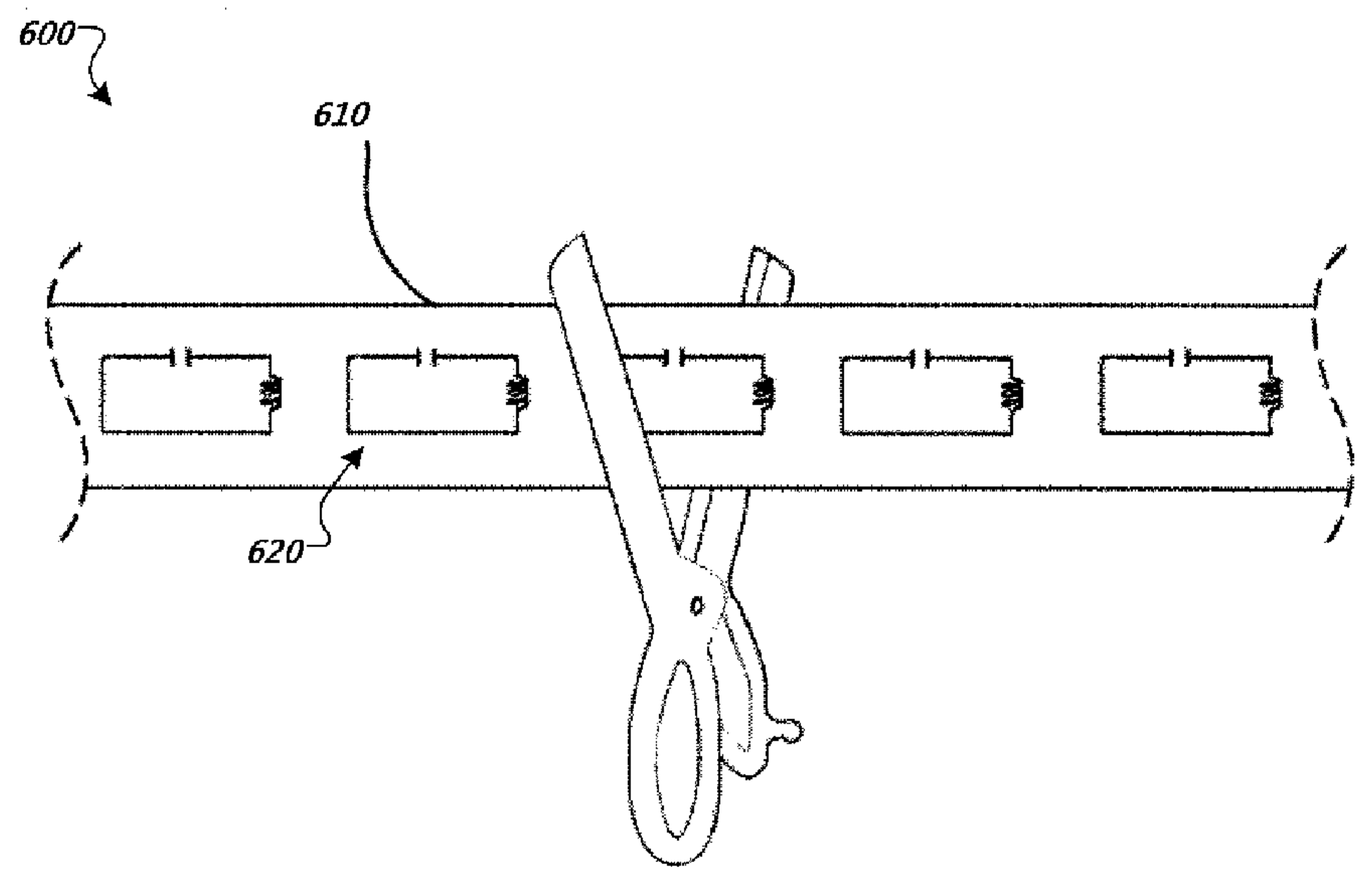


FIG. 24

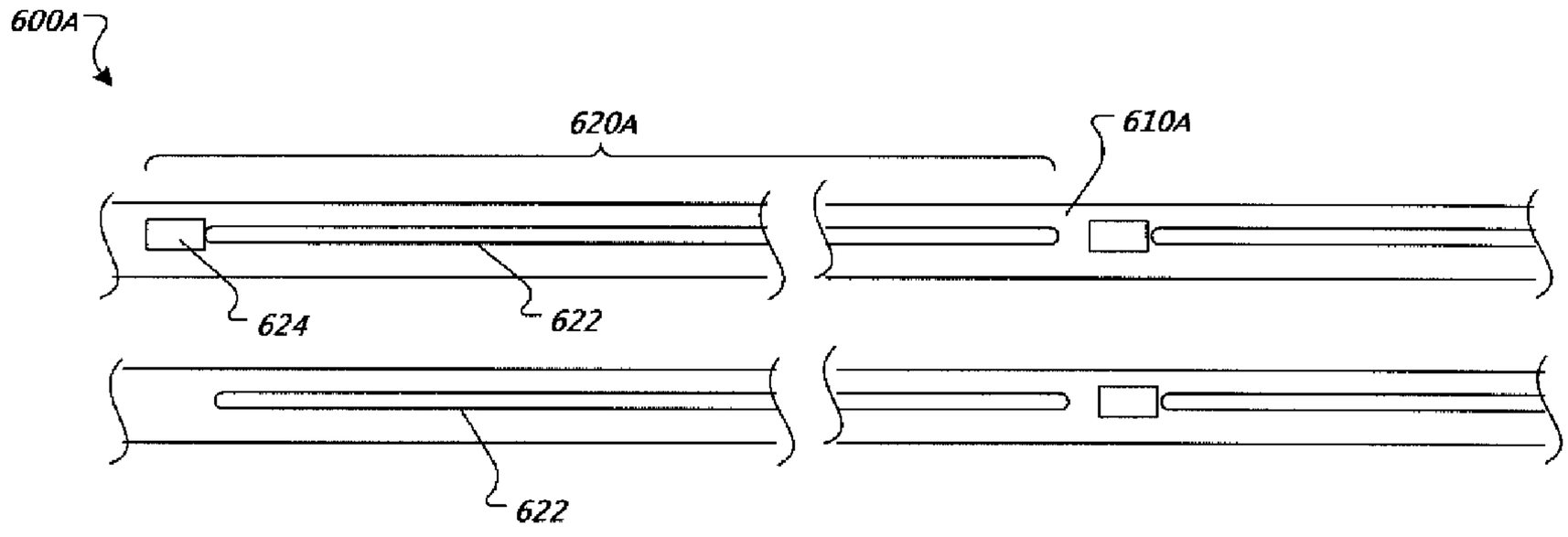


FIG. 25

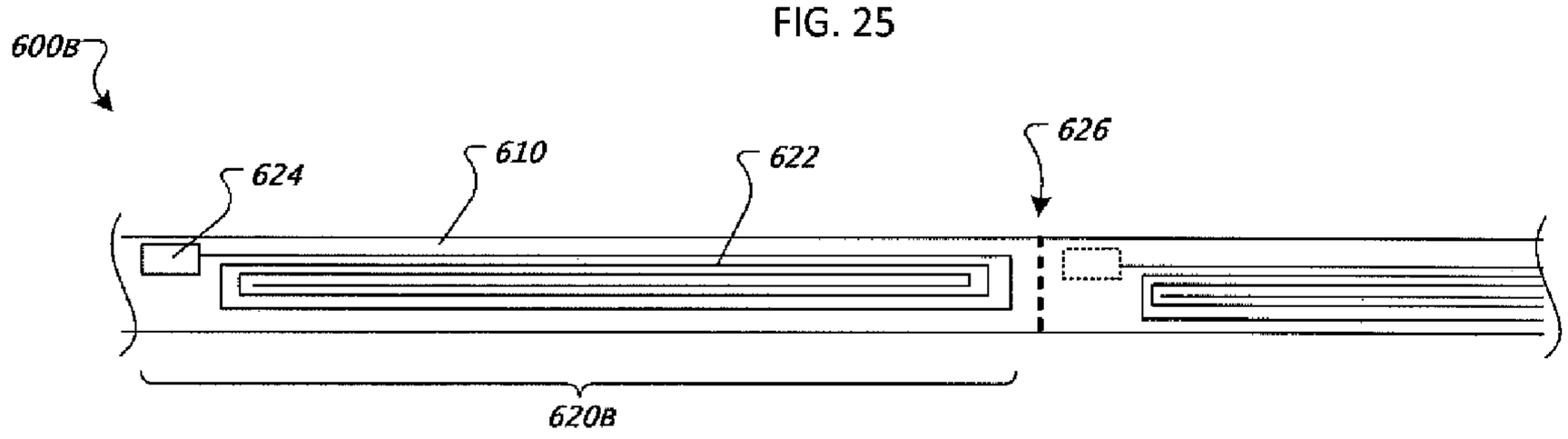


FIG. 26

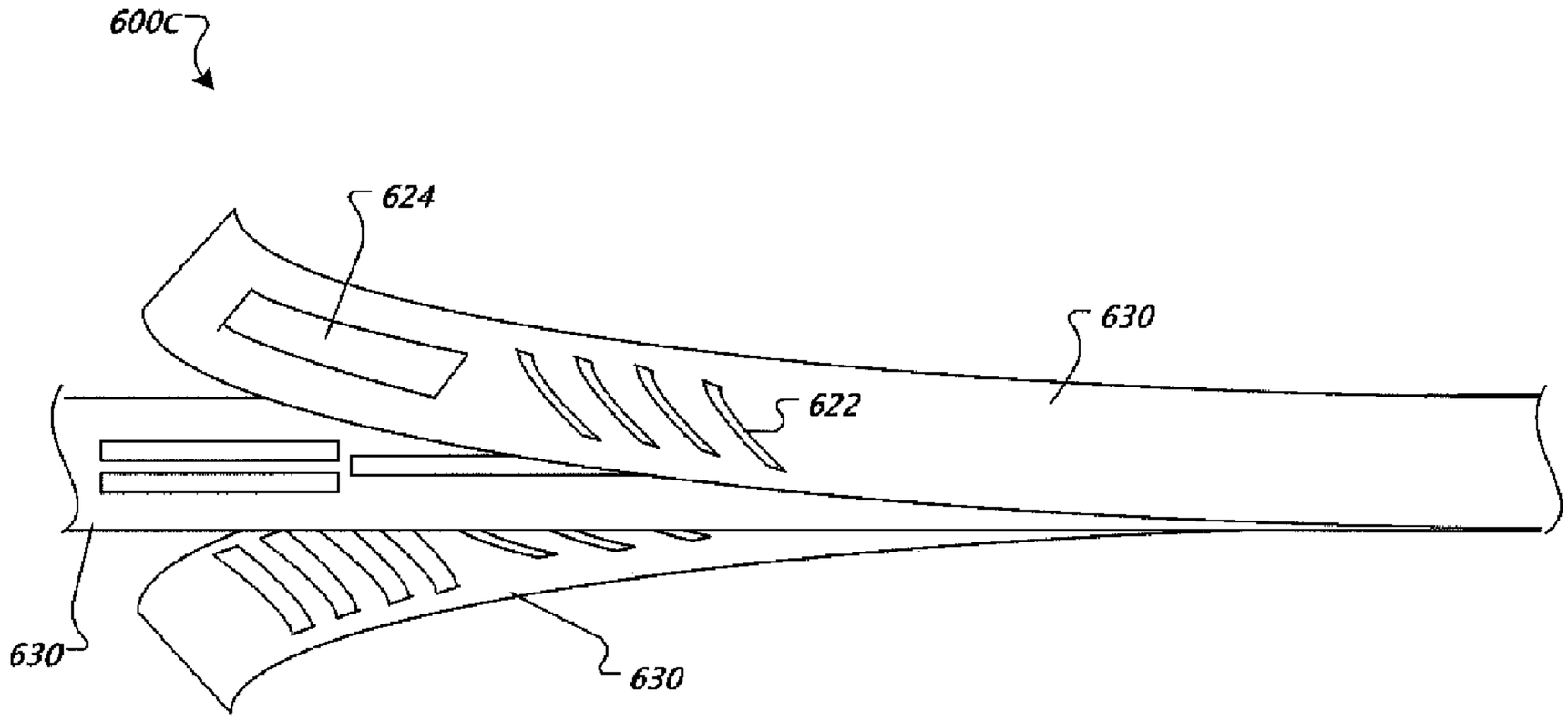


FIG. 27

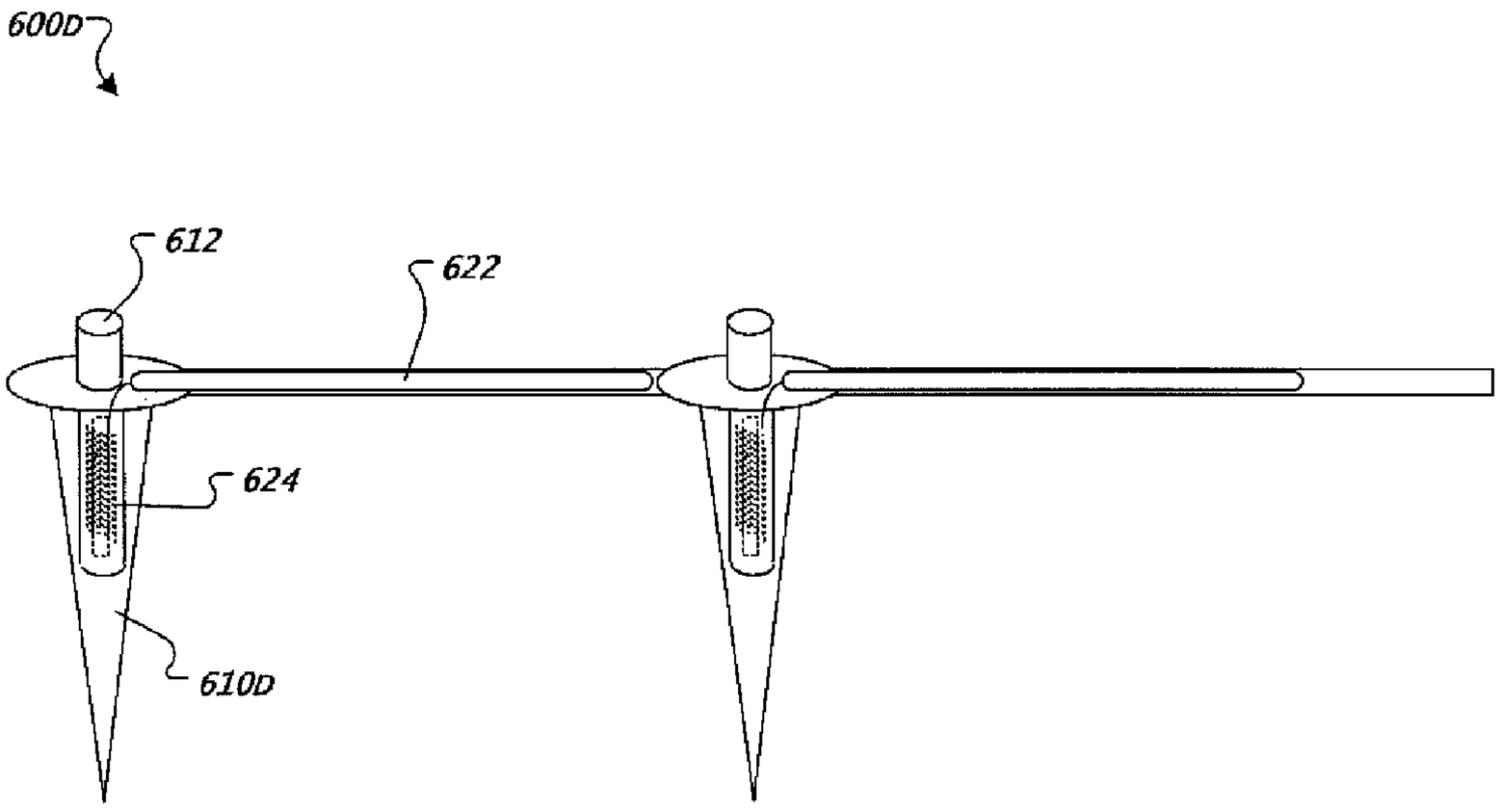


FIG. 28

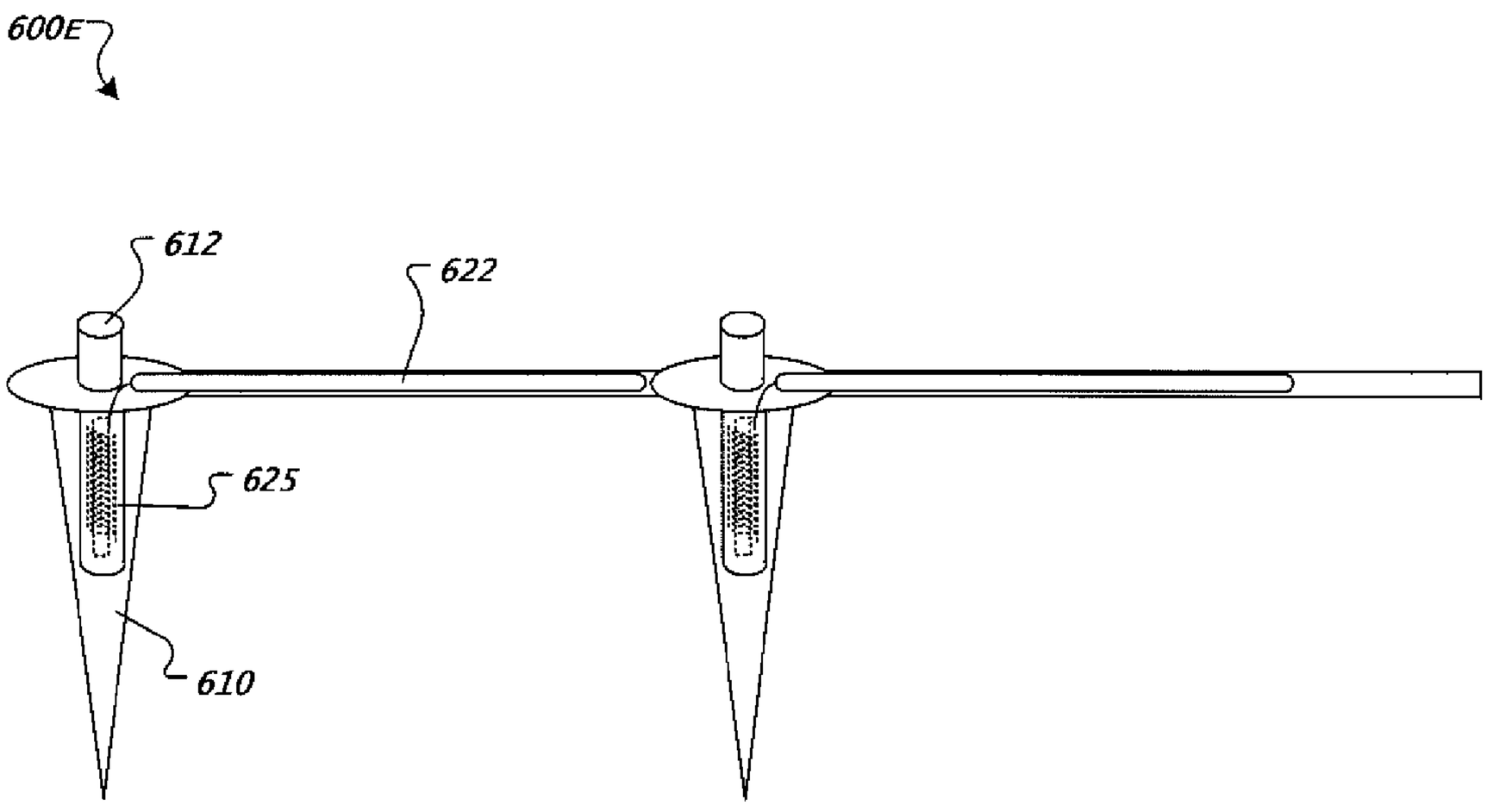


FIG. 29

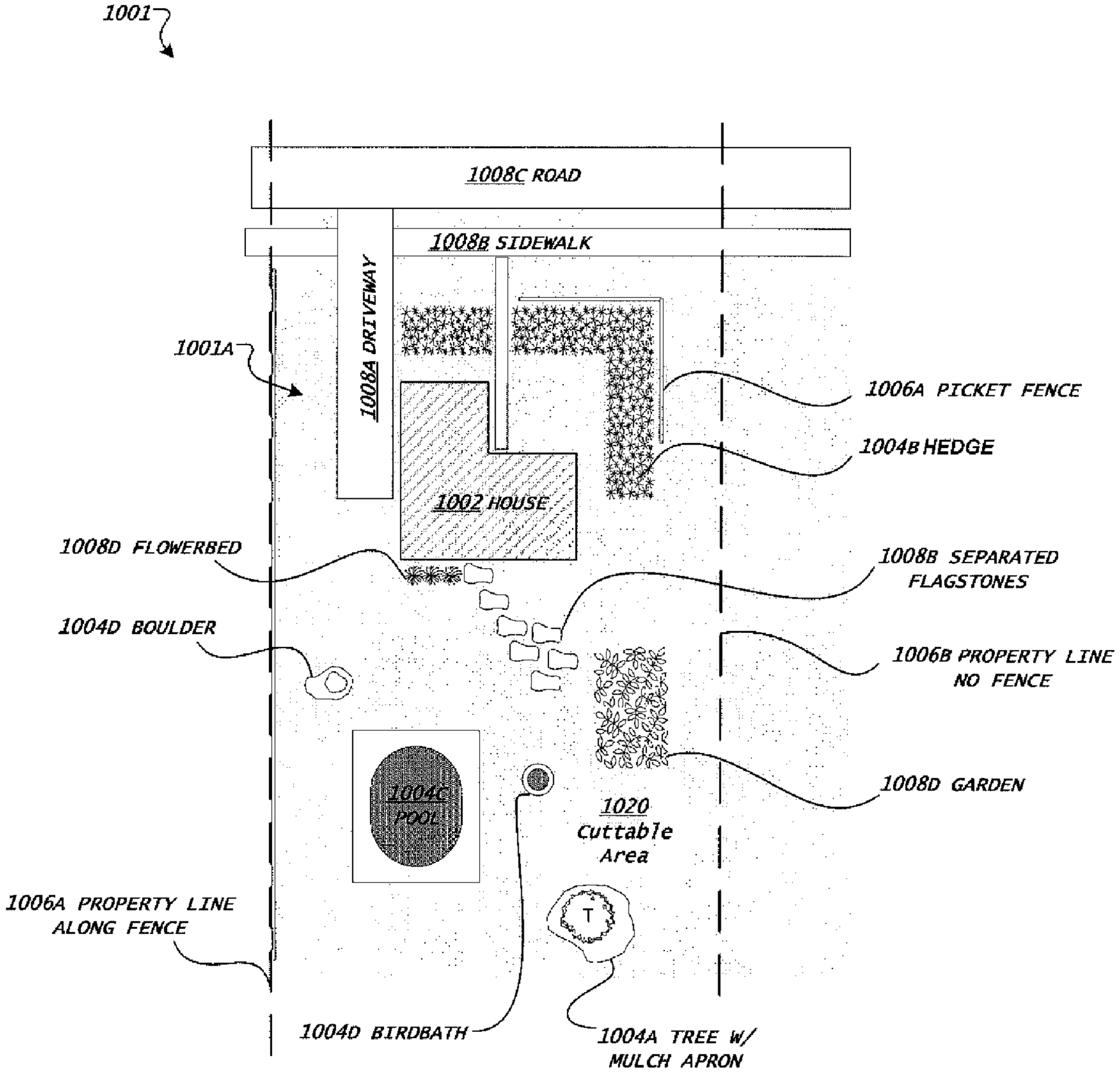

1001
1008C ROAD
1008B SIDEWALK
1008A DRIVEWAY
1001A
1006A PICKET FENCE
1004B HEDGE
1002 HOUSE
1008D FLOWERBED
1008B SEPARATED FLAGSTONES
1004D BOULDER
1006B PROPERTY LINE NO FENCE
1004C POOL
1020 Cuttable Area
1008D GARDEN
1006A PROPERTY LINE ALONG FENCE
1004D BIRDBATH
1004A TREE W/ MULCH APRON

FIG. 30

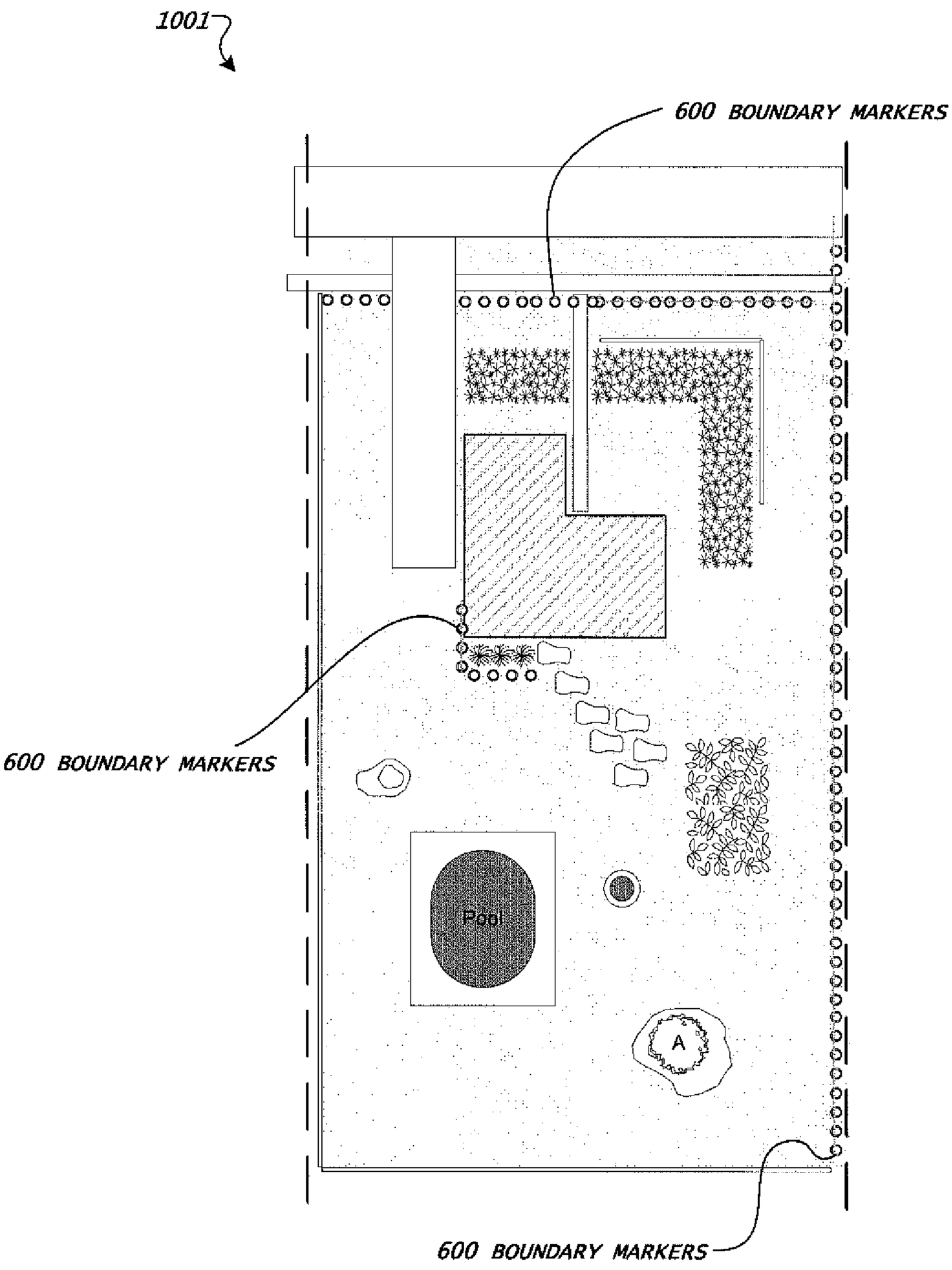

1001
600 BOUNDARY MARKERS
600 BOUNDARY MARKERS
Pool
A
600 BOUNDARY MARKERS

FIG. 31

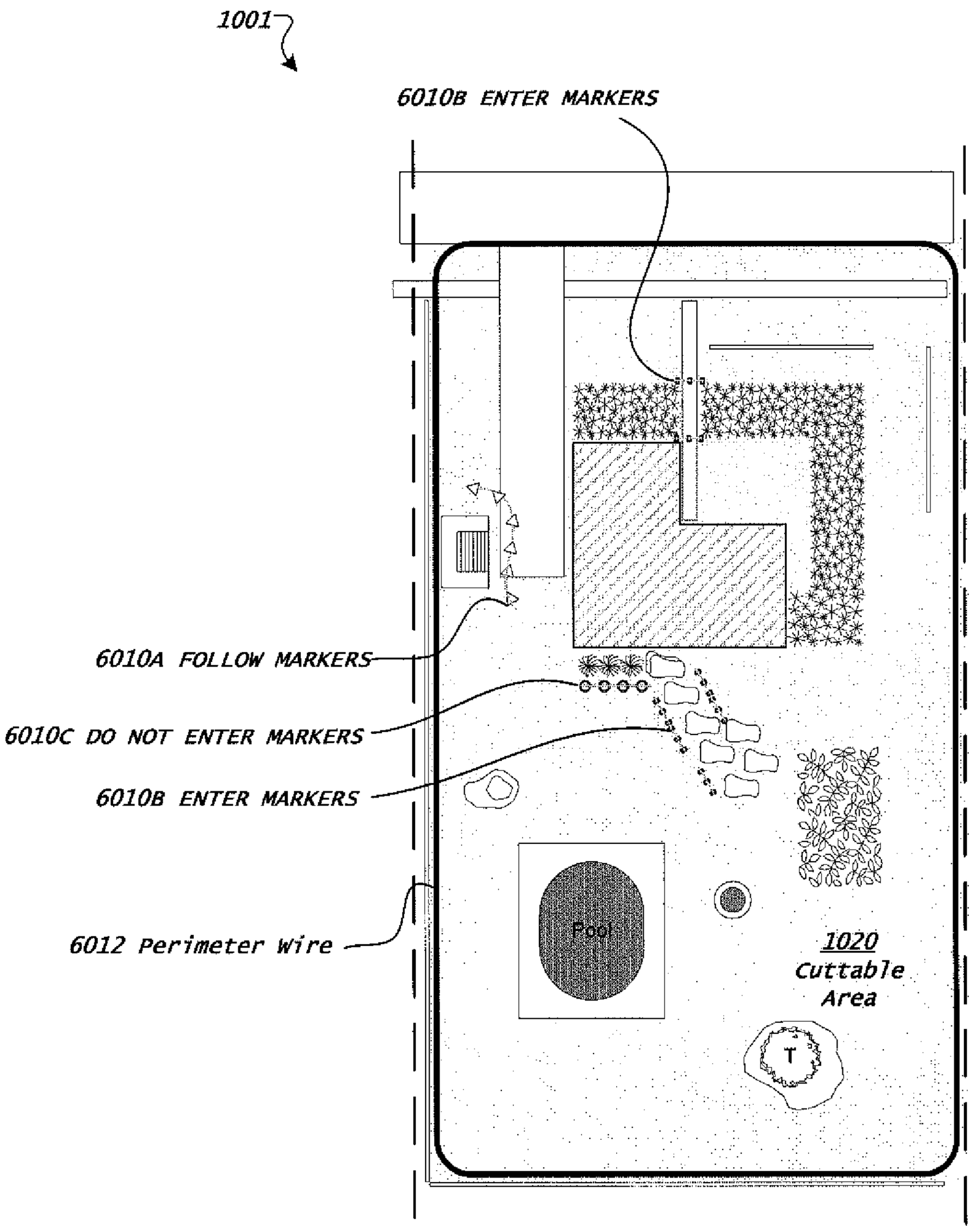

1001
6010B ENTER MARKERS
6010A FOLLOW MARKERS
6010C DO NOT ENTER MARKERS
6010B ENTER MARKERS
6012 Perimeter Wire
Pool
1020
Cuttable
Area
T

FIG. 32

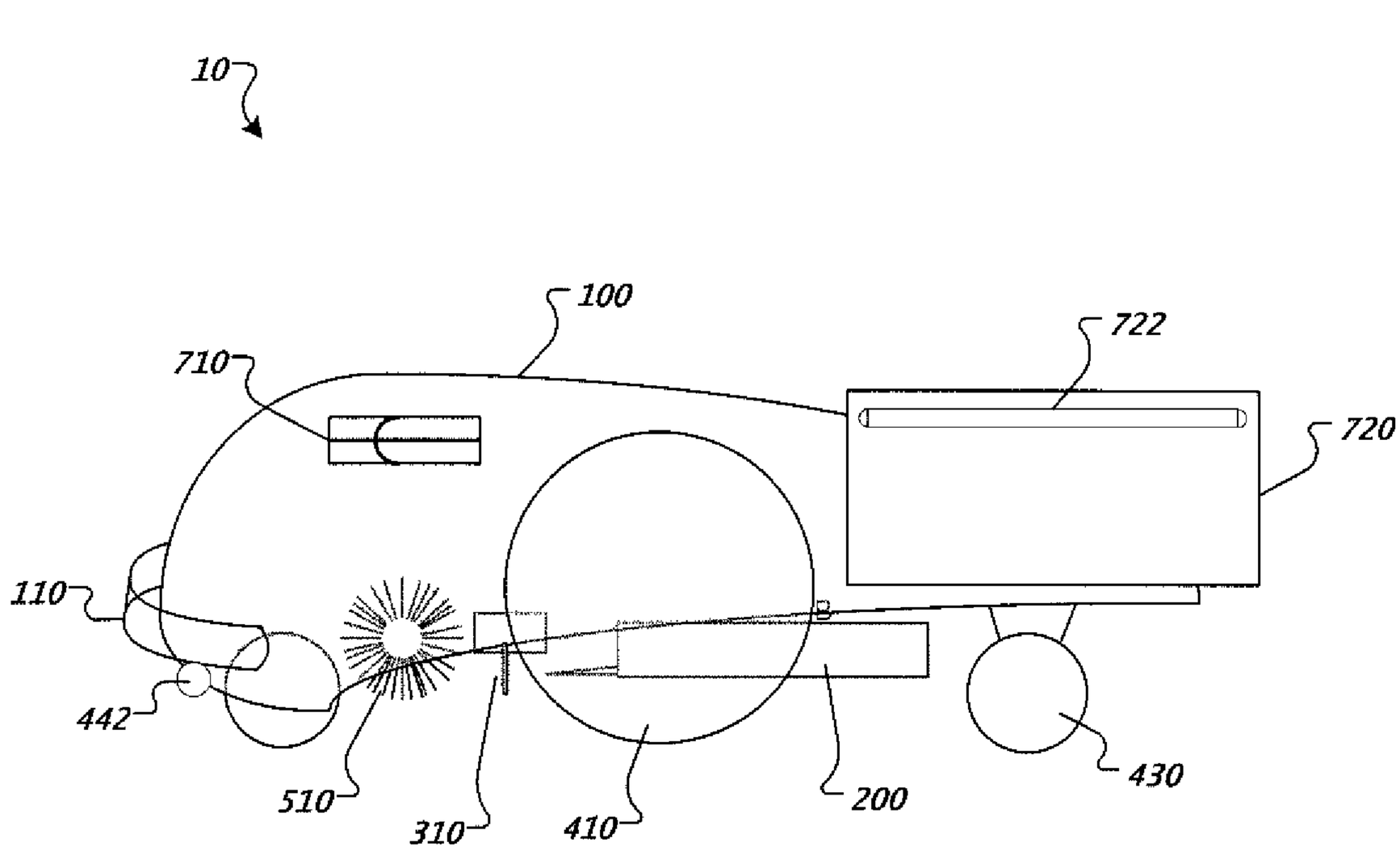


FIG. 33

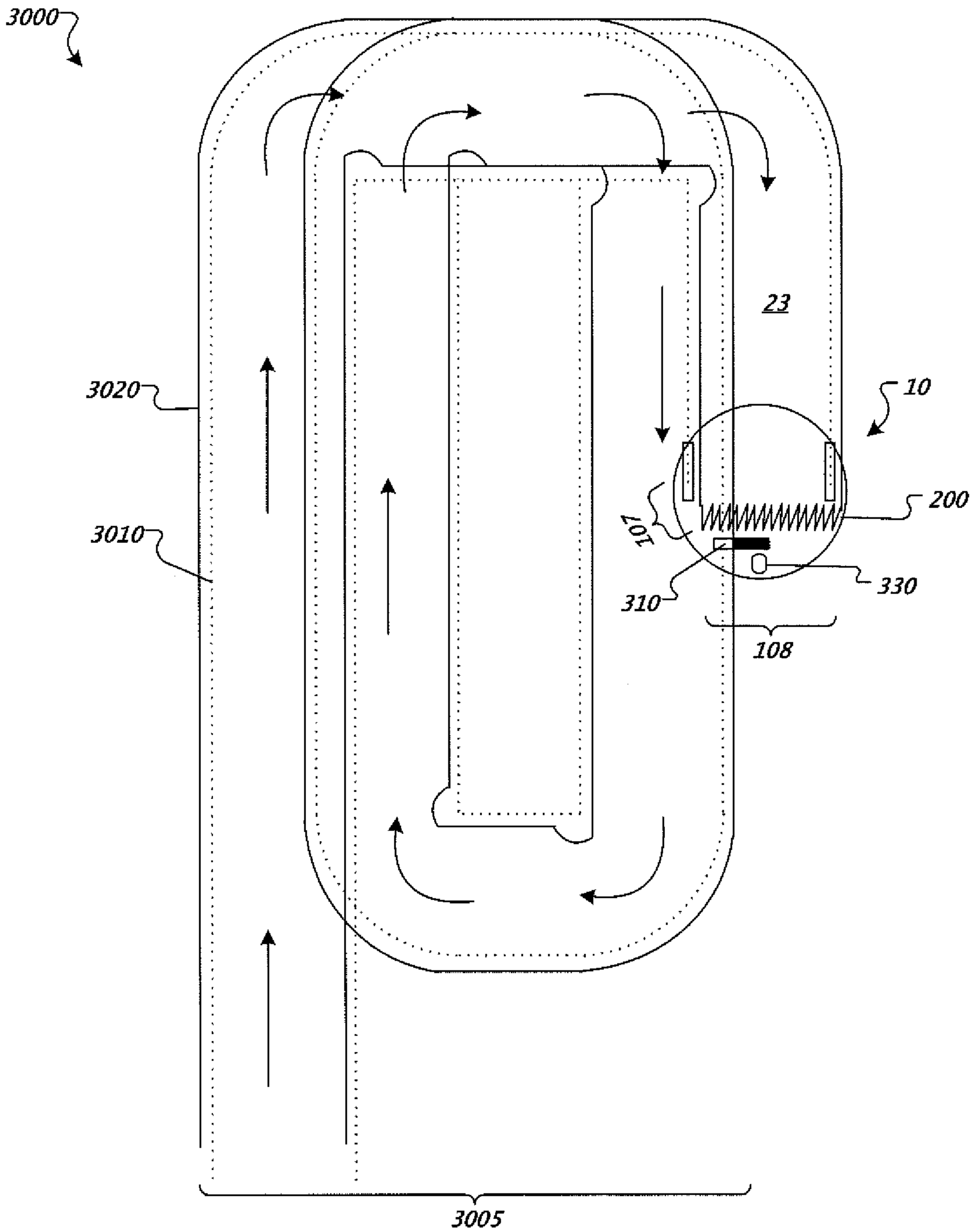


FIG. 34

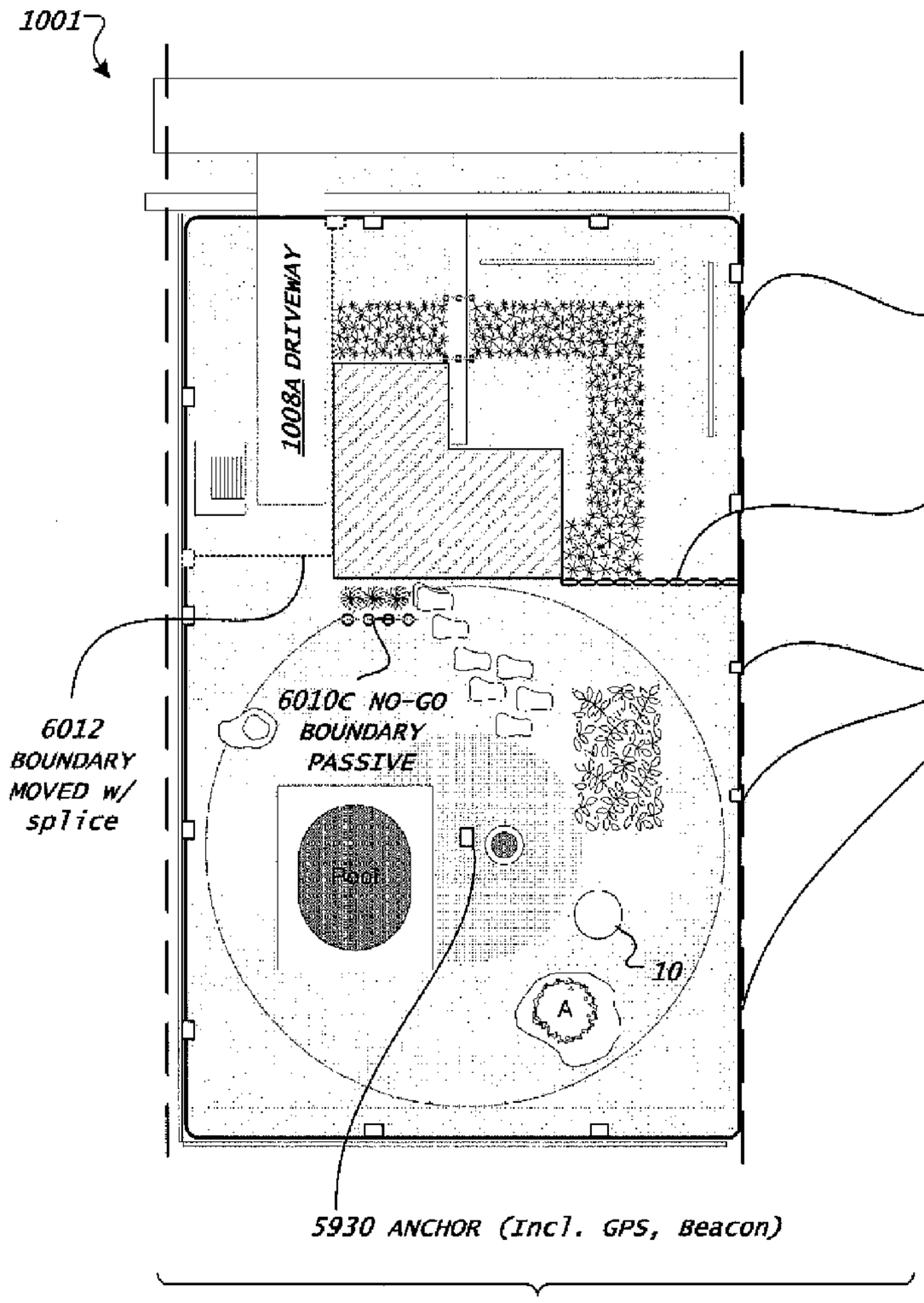


FIG. 35A

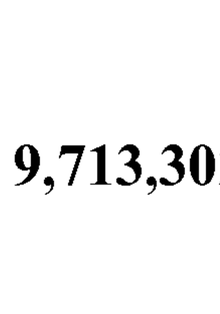


FIG. 35B

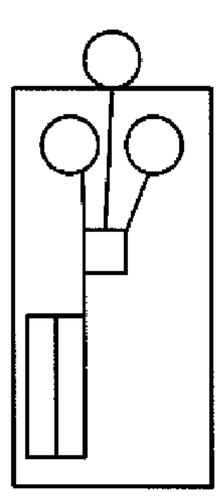


FIG. 35C

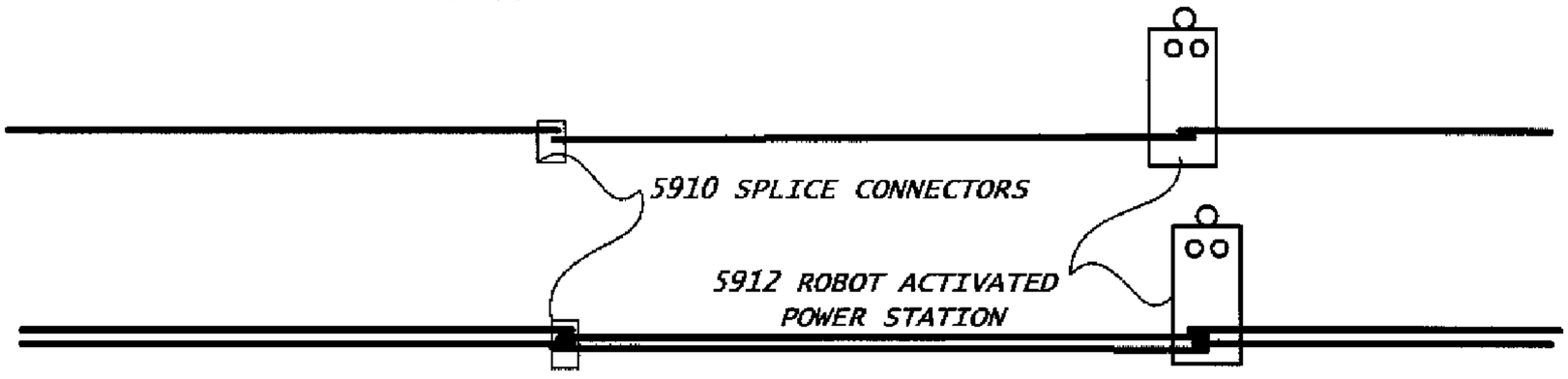


FIG. 35D

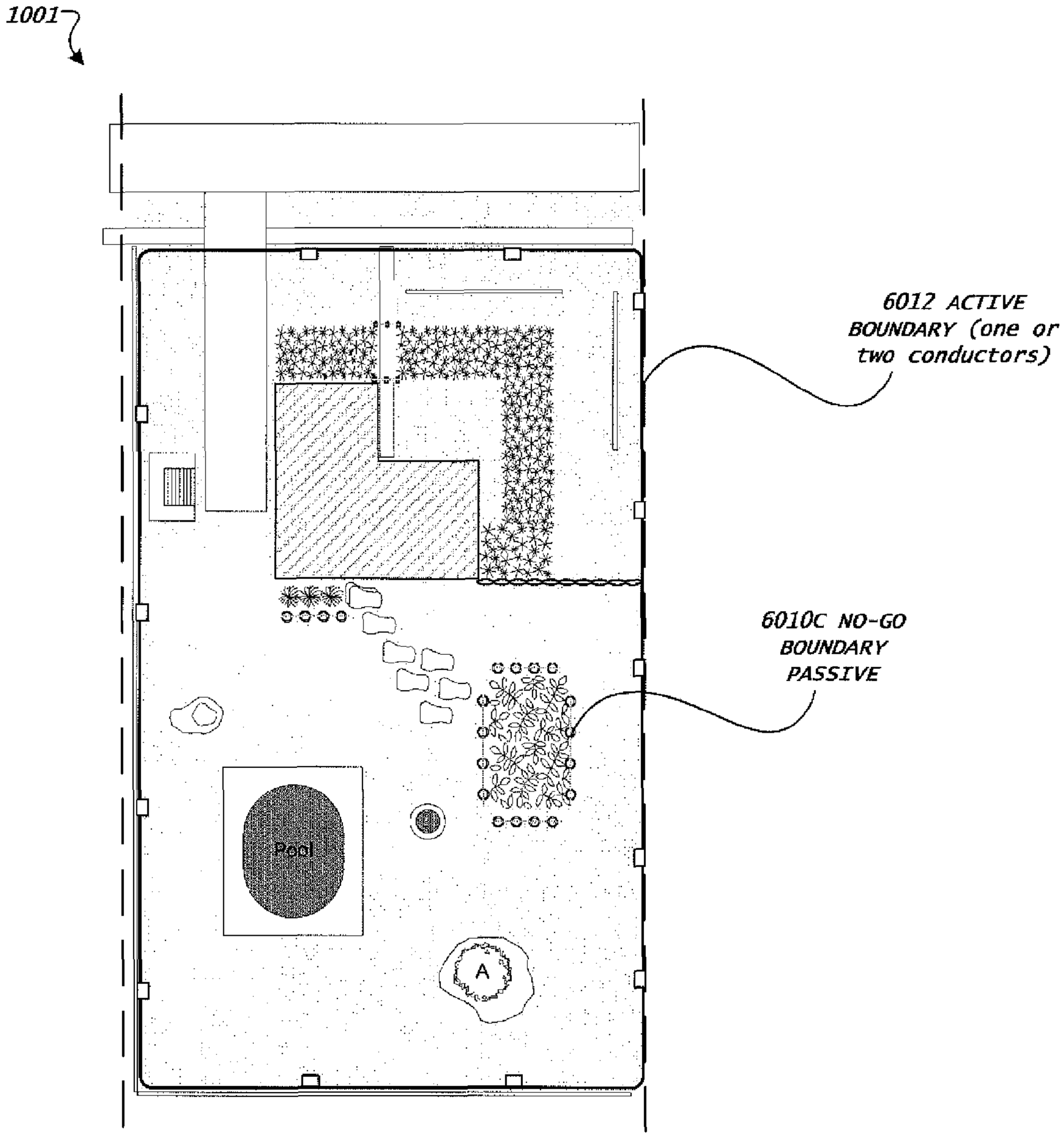

1001
6012 ACTIVE BOUNDARY (one or two conductors)
6010C NO-GO BOUNDARY PASSIVE
Pool
A

FIG. 36

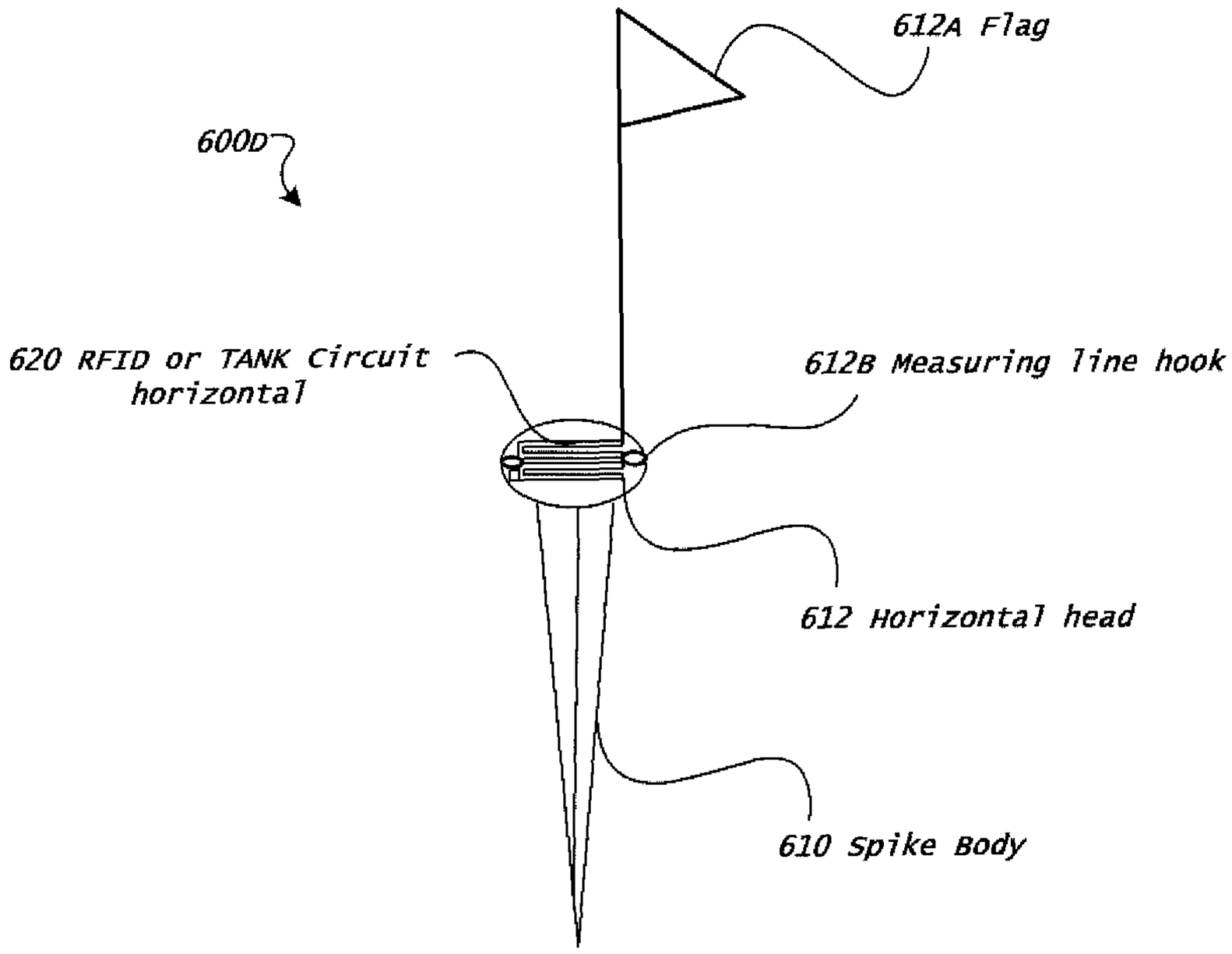

612A Flag
600D
620 RFID or TANK Circuit horizontal
612B Measuring line hook
612 Horizontal head
610 Spike Body

FIG. 37

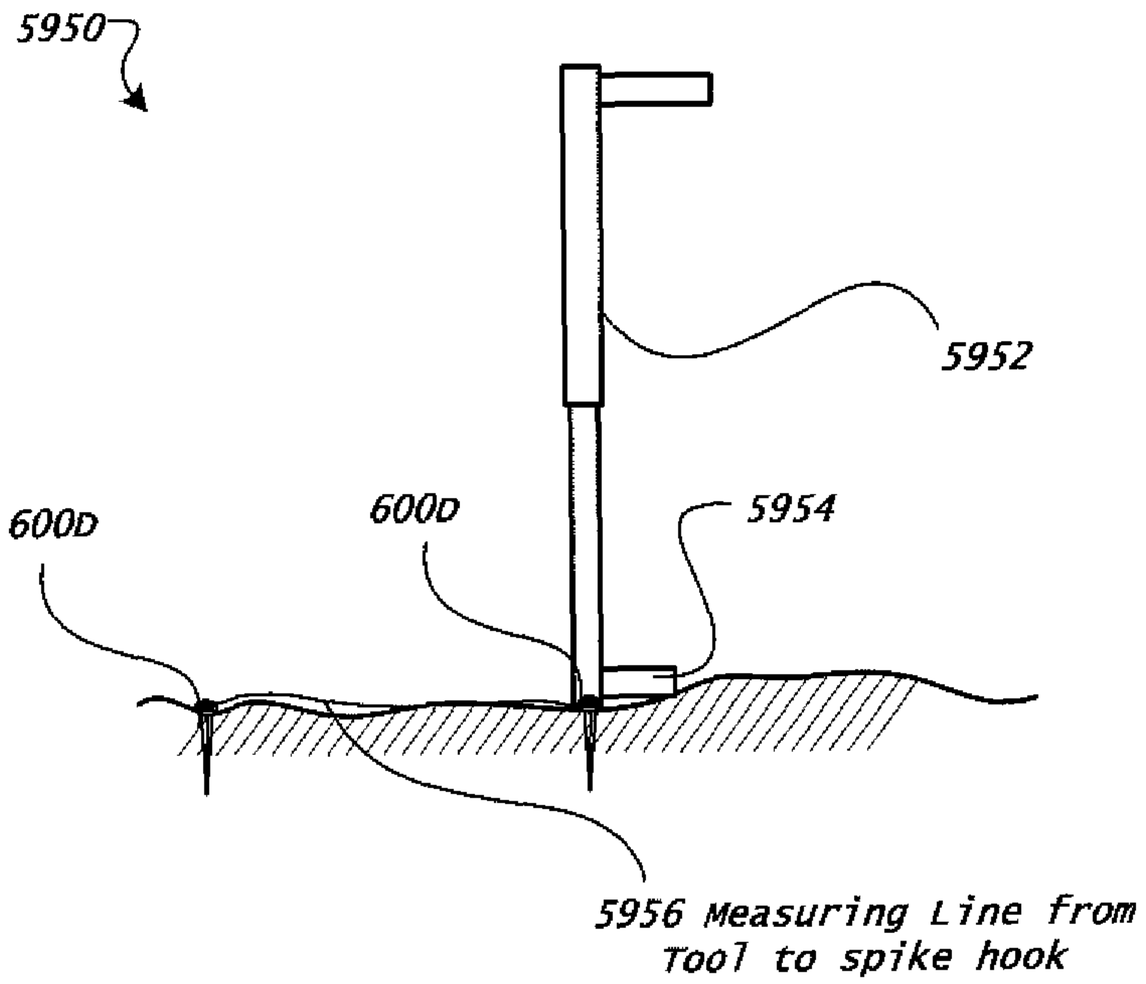

5950
5952
600D
600D
5954
5956 Measuring Line from Tool to spike hook

FIG. 38

ROBOT CONFINEMENT

This U.S. patent application claims priority under 35 U.S.C. 119(e) from U.S. provisional patent application 60/783,268, filed Mar. 17, 2006, and entitled "LAWN CARE ROBOT," from U.S. provisional patent application 60/803,030, filed May 23, 2006, and entitled "LAWNMOWER HAVING RECIPROCATING SHEARS," and from U.S. provisional patent application 60/865,069, filed Nov. 9, 2006, and entitled "HIGHLY MANEUVERABLE AUTONOMOUS PLATFORM." The entire contents of all three priority provisional applications are hereby incorporated by reference.

TECHNICAL FIELD

The disclosure relates to confinement of autonomous coverage robots, such as robots configured to perform cleaning or lawn care tasks.

BACKGROUND

Autonomous robots that perform household functions such as floor cleaning and lawn cutting are now readily available consumer products. Commercially successful robots are not unnecessarily complex, and generally operate randomly within a confined area. In the case of floor cleaning, such robots are generally confined within (i) touched walls and other obstacles within the rooms of a dwelling, (ii) IR-detected staircases (cliffs) down; and/or (iii) user placed detectable barriers such as directed IR beams, physical barriers or magnetic tape. Walls provide most of the confinement perimeter. Other, much less ubiquitous robots may try to localize or to map the dwelling using a complex system of sensors and/or active or passive beacons (e.g., sonar, RFID or bar code detection, or various kinds of machine vision).

There are examples of consumer robotic lawn mowers that use a similar "invisible" barrier—a continuous guide conductor boundary proposed for confining random motion robotic mowers by the early 1960's (See, e.g., U.S. Pat. Nos. 3,128,840; 3,550,714). Examples include commercial products by Electrolux, Husqvarna, Zucchetti S. A., Belrobotics, and Friendly Robotics. The guide conductor is intended to confine the robot within the lawn or other appropriate area, so as to avoid damaging non-grassy areas of the yard or intruding onto a neighboring property. The conductor is one continuous loop around the property to be mowed. Although the guide conductor can be drawn into the property in peninsulas to surround gardens or other off-limits areas, it remains a continuous loop, and is energized with an AC current detectable as a magnetic field at a few feet. The guide conductor must be supplied with power, usually from a wall socket. Within the bounded area, the known robots may "bounce" randomly as the robot nears the guide conductor, or may follow along the guide conductor. Some of the mowers also touch and bounce from physical barriers. More complex commercial mowers may try to localize or to map the mowing area, again using a complex system of sensors and/or active or passive beacons (e.g., sonar, encoded optical retro-reflector detection, machine vision).

SUMMARY

In one aspect, an autonomous coverage robot system includes an active boundary responder comprising a wire powered with an alternating current placed along a perimeter of a property, at least one passive boundary responder placed on a property interior circumscribed by the active boundary responder, and an autonomous coverage robot. The robot includes a drive system carried by a body and configured to maneuver the robot across the property interior. The robot includes a signal emitter emitting a signal, where the passive boundary responder is responsive to the signal and a boundary responder detection system carried by the body. The boundary responder detector is configured to redirect the robot both in response to the responder detection system detecting an active boundary responder and in response to detecting a passive boundary responder.

Implementations of this aspect of the disclosure may include one or more of the following features. The robot may include a grass cutter carried by the body. In some implementations, the boundary responder detector includes an emitter having an emitter antennae loop configured as a figure-eight and in communication with an emitter circuit and a receiver having a receiver antennae loop circumscribing and coplanar with the emitter antennae loop. The receiver antennae loop is in communication with a receiver circuit. A control circuit controls the emitter and receiver and is in communication with the drive system.

Upon recognizing the passive boundary responder, the robot maneuvers away from the boundary responder, in some examples, or over and follows the passive boundary responder, in other examples. In some implementations, the passive boundary responder includes a responder body and at least one excitable circuit carried by the responder body. The responder body may be an elongated substrate or define a spike. In one implementation, the passive boundary responder includes at least one inductive circuit and a load element to set a resonant frequency. In another implementation, the passive boundary responder includes at least one capacitive circuit and a load element to set a resonant frequency. In other implementations, the passive boundary responder includes amorphous metal or a radio frequency identification unit.

In some implementations, the robot includes a global positioning system carried by the body and configured to periodically compare an ascertained global position with a property interior position. The robot may include a bumper carried by the body and housing a contact sensor configured to detect contact with the bumper. The robot may include a proximity sensor carried by the body and configured to detect a potential obstacle proximate the robot. The proximity sensor includes an emitter and a receiver. The emitter projecting an emission and the receiver configured to detect the emission reflected off a potential obstacle. The robot may also include a liquid sensor responsive to bodies of liquid proximate the robot. The liquid sensor includes a light emitter emitting light downwardly and a receiver configured to detect reflected light.

In some examples, the robot includes a hard surface detector carried by the body and responsive to hard surfaces. The drive system is configured to redirect the robot in response to the detector detecting a hard surface. The hard surface detector includes a sensor housing defining emitter and receiver receptacles. An audio transmitter is carried in the emitter receptacle and transmits an audio emission. A receiver is carried in the receiver receptacle and is configured to receive an audio emission reflected off a ground surface. A controller of the robot compares a received reflected audio emission with a threshold energy to detect a hard surface. The audio transmitter transmits multiple audio emissions starting at a fundamental frequency and successively increasing the wavelength of each emission by half

the fundamental frequency. The audio transmitter transmits a first audio emission at about 6.5 kHz and a second audio emission at about 8.67 kHz. The controller receives the reflected audio emission from the receiver though a narrow band-pass amplifier. An anti-vibration mounting system secures the receiver in the receiver receptacle. The anti-vibration mounting system includes a first elastic support holding the receiver in a tube below a sound absorber. The tube is secured in the receiver receptacle with a second elastic support having a lower durometer than the first elastic support.

In some examples, the robot includes a grass detector having four different colored narrow-spectrum light emitters and an optical receiver receiving reflected light from the emitters. The optical receiver is configured to detect grass by evaluating the received light.

In some examples, the robot includes a surface detector responsive to a surface pH, surface capacitance, or surface color. In some examples, the robot includes four different colored narrow-spectrum light emitters and an optical receiver receiving reflected light from the emitters. The optical receiver is configured to detect grass by evaluating the received light.

In another aspect, a method of navigating a property with an autonomous coverage robot includes placing an active boundary responder along at least a portion of a perimeter of the property, powering the active boundary responder with an electrical voltage, placing at least one passive boundary responder within the property, placing the robot within the property, and permitting the robot to navigate the property while the drive system redirects the robot in response to encountering the active boundary responder to keep the robot within the property, and redirects the robot in response to encountering the passive boundary responder within the property. The robot includes a body, a drive system carried by the body and configured to maneuver the robot across the property interior, and a signal emitter emitting a signal. The passive boundary responder is responsive to the signal. The robot includes a boundary responder detector carried by the body and configured to detect both the active and passive boundary responders. The drive system is configured to redirect the robot in response to detecting an active boundary responder and in response to detecting a passive boundary responder.

Implementations of this aspect of the disclosure may include one or more of the following features. The boundary responder detector includes an emitter having an emitter antennae loop configured as a figure-eight and is in communication with an emitter circuit and a receiver having a receiver antennae loop circumscribing and coplanar with the emitter antennae loop. The receiver antennae loop is in communication with a receiver circuit. A control circuit controls the emitter and receiver and is in communication with the drive system.

In yet another aspect, an autonomous coverage robot includes a body, a drive system carried by the body and configured to maneuver the robot across a surface, and an acoustic surface sensor carried by the body. The acoustic surface sensor includes a sensor housing defining emitter and receiver receptacles. An audio transmitter is carried in the emitter receptacle and transmits an audio emission. A receiver is carried in the receiver receptacle and is configured to receive an audio emission reflected from the surface. A controller monitors a received reflected audio emission and compares a maximum receive energy with a threshold energy to classify the surface.

Implementations of this aspect of the disclosure may include one or more of the following features. The audio transmitter transmits multiple audio emissions starting at a fundamental frequency and successively increasing the wavelength of each emission by half the fundamental frequency. The audio transmitter transmits a first audio emission at about 6.5 kHz and a second audio emission at about 8.67 kHz. The controller receives the reflected audio emission from the receiver though a narrow band-pass amplifier. An anti-vibration mounting system secures the receiver in the receiver receptacle. The anti-vibration mounting system includes a first elastic support holding the receiver in a tube below a sound absorber. The tube is secured in the receiver receptacle with a second elastic support having a lower durometer than the first elastic support.

In another aspect, a method of classifying a surface below an autonomous coverage robot includes transmitting an audio emission below the robot, receiving an audio emission reflected off a ground surface, increasing a frequency of the audio emission by half a fundamental frequency, and comparing a maximum receive energy of the reflected emission with a threshold energy to classify the surface.

The details of one or more implementations of the disclosure are set fourth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a schematic view of lawn care robots.

FIG. **1**B is a schematic view of a method of lawn cutting with a robotic lawnmower.

FIGS. **2**A-**2**C are schematic views of lawn care robots.

FIGS. **3**A-**3**K are schematic and block diagram views of lawn care robots.

FIG. **4**A is a side view of a lawn care robot.

FIG. **4**B is a rear view of a lawn care robot.

FIG. **4**C-D are top views of a lawn care robot.

FIG. **4**E is a side view of a lawn care robot.

FIG. **4**F is a rear view of a lawn care robot.

FIG. **4**G is a top view of a lawn care robot.

FIG. **4**H is a side view of a lawn care robot.

FIG. **4**I is a top view of a lawn care robot.

FIG. **4**J is a side view of a drive wheel of a lawn care robot.

FIG. **4**K-N are front views of a drive wheel of a lawn care robot.

FIG. **5**A is a schematic view of a rotary cutter.

FIG. **5**B is an exploded view of a rotary cutter.

FIGS. **5**C-D are schematic views of a reciprocating cutter.

FIG. **5**E is a schematic view of a comb of a reciprocating cutter.

FIGS. **5**F-G are schematic views of a reciprocating cutter.

FIGS. **5**H-I are schematic views of cutters.

FIG. **6**A is a schematic view of a hybrid mechanical-electric robotic mower system.

FIG. **6**B is a schematic view of an all electric robotic mower system.

FIG. **6**C is a schematic view of a robotic mower system.

FIG. **6**D is a table of components for a robotic mower system.

FIG. **6**E is a schematic view of grass-cutting obstacles, boundaries, and cuttable areas in a neighborhood.

FIGS. **7**A-B are schematic views of methods of navigating a mower.

FIG. **7**C is a schematic view of a robotic mower and a handle.

FIG. **7**D is a schematic view of a robotic mower with a handle.

FIG. **7**E is a schematic view of a robotic mower with a stowed handle.

FIG. **7**F is a schematic view of a robotic mower with a handle.

FIG. **8**A is a schematic view of an optical not-grass detector.

FIG. **8**B is a diagram illustrating an example response of an optical not-grass detector over time.

FIGS. **8**C-D are schematic views of acoustic not-grass detectors.

FIG. **8**E is a schematic view of an acoustic hard surface detector.

FIG. **8**F is a diagram of a process of classifying a target surface with an acoustic hard surface detector.

FIG. **8**G is a schematic view of a mounting system for an emitter or receiver of an acoustic hard surface detector.

FIG. **9** is a schematic view of a liquid detector.

FIG. **10** is a schematic view of a cut edge detector.

FIGS. **11**A-B are schematic views of cut edge detectors.

FIG. **12** is a rear schematic view of a lawn care robot having a cut edge detector and a calibrator.

FIG. **13** is a schematic view of a cut edge detector.

FIG. **14** is a schematic view of an optical sensor.

FIG. **15**A is a schematic view of a cut edge detector.

FIG. **15**B is a top schematic view of a lawn care robot.

FIG. **16**A-B are schematic views of cut edge detectors.

FIG. **16**C is a schematic view of a grass height row vector.

FIG. **16**D is a schematic view of a two-dimensional grass height row vector array.

FIG. **16**E is a schematic view of a grass height image from a cut edge detector.

FIGS. **17-19** are schematic views of cut edge detectors.

FIG. **20** is a rear schematic view of a lawn care robot having a cut edge detector and a calibrator.

FIGS. **21-22** are schematic views of cut edge detectors.

FIG. **23**A is a schematic view of a lawn care robot system and mowing robot encountering a boundary responder.

FIG. **23**B is a schematic view of boundary responder detector for a lawn care robot system.

FIGS. **24-29** are schematic views of boundary responders.

FIG. **30** is a schematic view of a property having boundaries, obstacles, cuttable areas, and non-cuttable areas.

FIG. **31** is a schematic view of a property having boundary responders.

FIG. **32** is a schematic view of a property having follow and enter responders.

FIG. **33** is a schematic view of a lawn care robot.

FIG. **34** is a schematic view of an example cutting pattern mowed by a lawn care robot.

FIG. **35**A is a schematic view of a property with a perimeter boundary having splice connectors, power stations, and an anchor.

FIG. **35**B is a schematic view of a splice connector.

FIG. **35**C is a schematic view of a robot-activated power station.

FIG. **35**D is a schematic view of a perimeter boundary having splice connectors and power stations.

FIG. **36** is a schematic view of a property with a perimeter boundary having splice connectors, power stations, and boundary responders.

FIG. **37** is a schematic view of a spike type boundary responder.

FIG. **38** is a schematic view of a spike type boundary responder installation tool.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

An autonomous robot may be designed to clean flooring. For example, the autonomous robot may vacuum carpeted or hard-surfaces and wash floors via liquid-assisted washing and/or wiping and/or or electrostatic wiping of tile, vinyl or other such surfaces. U.S. Pat. No. 6,883,201 by Jones et al. entitled AUTONOMOUS FLOOR CLEANING ROBOT, the disclosure of which is herein incorporated by reference it its entirety, discloses an autonomous cleaning robot. Notwithstanding the use of the term mowing robot herein, these concepts may also apply to a cleaning or other coverage robot.

Referring to FIGS. **1-3**, an autonomous coverage robot **10** includes a body **100**, a surface treater **200** secured to the body **100**, and at least one surface sensor **310**, **320**, **330** carried by the body **100** and responsive to at least one surface characteristic. A drive system **400** is carried by the body **100** and configured to maneuver the robot **10** across a surface **20** while following at least one surface characteristic. Examples of the surface treater **200** include a reciprocating symmetrical cutter floating on a following wheel **210**, a rotary cutter, a spreader, and a gatherer. The body **100**, as shown in FIG. **1**A, has a substantially circular perimeter; however, other shapes are suitable as well, such as a substantially pentagonal, tombstone, or rectangular shape, as shown in FIGS. **2**A-**3**. In some implementations, the robot **10** comprises a frame-and-body structure or a substantially monocoque structure. In some implementations, the body **100** includes a two part articulated body, which will be described later in detail.

In some examples, one or more edge following sensors **310** (also referred to as cut edge detectors) and edge calibrators **320** (e.g. a grass character sensor) are mounted on the body **100**. FIG. **1**A depicts an exemplary placement of boundary sensors **340**, a bumper **110** (which may be coupled to two or more displacement sensors to provide impact directionality) and at least one grass sensor **330** (e.g. determines a presence of grass) on the body **100**. An active or passive fore grass comber **510** precedes the surface treater **200** and an aft grass comber **520** follows each wheel **410**, **420**, **430**.

Referring to FIG. **1**B, a method of lawn cutting with a robotic lawnmower **10** having a drive system **400** and a cutter **200** carried by a body **100** includes step S**10** of activating the drive system **400** to maneuver the robotic lawnmower **10** across a lawn **20**, step S**30** of detecting a swath edge **26** with the swath edge detector **310**, and step S**40** of following a detected swath edge. The method may include step S**20** of orienting blades of grass of the lawn **20** with a grass arranger **440** carried by the body **100** forward of a swath edge detector **310** carried by the body **100**. The method includes step S**50** of erecting blades of grass of the lawn **20** with a fore grass comber **510** carried by the body forward **100** of the cutter **200**, step S**60** of cutting the lawn **20** with the cutter **200**, and step S**70** of arranging blades of grass of the lawn **20** with an aft grass comber **520** carried by the body **100** rearward of the cutter **200** and/or the drive system **400**. In some examples, the method includes one or more of the following steps: step S**80** of continuously scanning for an absence of lawn **20** with a lawn detector **330** carried by the body **10**, where the drive system **400** redirects

the robot **10** in response to detecting an absence of lawn **20**; step S**90** of continuously scanning for a body of liquid **1004**C proximate the robot **10** with a liquid detector **350** carried by the body **100**, where the drive system **400** redirects the robot **10** in response to detecting a body of liquid **1004**C; step S**100** of continuously scanning for a potential obstacle proximate the robot **10** with a proximity sensor (e.g. infrared sensor) carried by the body **100**, where the drive system **400** redirects the robot **10** in response to detecting a potential obstacle; and step S**110** of continuously scanning for a boundary responder **600** with a boundary detector **1500** carried by the body **100**, where the drive system **400** redirects the robot **10** in response to detecting a boundary responder **600**.

A configuration and height of the bumper **110**, in some instances, are arranged according to a ground clearance or a cut height of the cutter **200**. The bumper height may be lower than the cut height of the cutter **200**. Also, the bumper **110** may rise and lower with the cutter **200**.

In one example, the drive system **400** includes left and right driven wheels, **410** and **420** respectively, and a trailing wheel **430** (e.g. a caster). In one implementation, the drive system **400** includes at least one drive wheel **410**, **420** rotated by a motor or other drive mechanism (e.g. an electric motor supplied power from a consumer-level battery, fuel cell, large capacitors, microwave receiver, an internal/external combustion engine powered by an onboard fuel source, hydraulic/pneumatic motor powered by an above aforementioned power source, large potential energy sources such as wound or compressed springs such as in hydraulic or pneumatic, vacuum accumulators, flywheels, or compressed air). In some instances, the drive system **400** includes a differential drive on a center axis **105** with two independently driven wheels **410**, **420**. One or more of the wheels **410**, **420**, **430** may swivel to aid navigation or adjustment of yaw of the robot **10**. In other implementations, the drive system **400** includes a holonomic drive, particularly in combination with a body **100** having a shape of constant width. The robot **10** may rotate about more than one point within an area defined by an outline of the body **100**, thereby escaping from, traversing, or otherwise avoiding entrapment in spaces approaching a width of the robot **10**.

Typically, the robot **10** is used on a yard or lawn **20**. Referring again to the example of FIG. **1**A, as the robot **10** mows the lawn **20**, an uncut area **22** is generally longer than a cut area **24**. After mowing an initial swath **23**, which may be linear, circular, or some other geometry, the robot **10** follows a swath edge **26** (i.e. the boundary edge between the uncut and cut areas, **22** and **24** respectively) for each successive swath **23**. If the initial swath **23** is circular or arced, the robot edge following will result in an emergent spiraling path. If the initial swath **23** is linear, upon reaching the end of a swath **23**, the robot **100** rotates approximately 180 degrees, aligns itself with the swath edge **26** using the cut edge detector **310**, and proceeds to mow another swath **23**. The robot **10** successively repeats this process until it determines that it has completed mowing the yard **20**, for example, or until it reaches some other state which ends a mowing cycle. By aligning itself to the immediately preceding mowed swath **23**, the robot **10** may ensure that it mows the lawn **20** in a generally uniform pattern of adjacently cut swaths **23**, achieving a mowed appearance similar to a lawn **20** mowed by conventional devices. By relying on the cut edge detector **310** to continuously realign the robot's heading based as it mows each successive adjacent swath **23**, the robot **10** may forgo using other more complex equipment for alignment, such as GPS, triangulation, inertial, and odometric reckoning, requiring additional sensors and/or processing power.

Each of the examples shown in FIGS. **1-4** share relatively large diameter differential drive wheels **410**, **420** (e.g., 8 inches or greater), casters **430**, **440** of a lesser diameter, and optional fore and aft grass combers/lifters, **510** and **520** respectively.

FIGS. **2**A-C depict alternative implementations of the lawn care robot **10** having a substantially pentagonal shape of constant width in which the widest portion trails the center axis **105**. Each robot **11**, **12** includes a differential drive off, near to, or on the center axis **105** and an asymmetrical reciprocal cutter **200**A. Separate edge following sensors **310** and grass character sensors **320** are provided in pairs (although only one of each is optional). FIGS. **2**A and **2**B also illustrate alternative locations of the fore and aft grass combs, **510** and **520** respectively, and the calibration sensors **320**. A caster **430** or fixed bearing auxiliary wheel **440** may depress the grass. Example locations of the grass depressing wheel **430**,**440** include forward or rearward of one cut edge detector **310**, forward of a first cut edge detector **310** and rearward of a second cut edge detector **310** (shown between in FIG. **2**A), forward of the cutter **200** (shown ahead in FIG. **2**B), and rearward of the cutter **200**.

Referring to FIG. **2**A, a robot **11** (which is configured as the robot in FIG. **33**) includes one trailing caster **430** and a cutter **200**A carried by the body **100**. The cutter **200**A has a blade extending to an uncut side **101** edge of the robot **11**. A fore grass comber **510** carried by the body **100** is shown with a relatively larger front to back size to accommodate a rotating bar bearing strings, filaments, chains, tines, bristles, flexible flaps, or a combination of these. The fore grass comber **510** is shown optionally laterally adjacent a grass depressing wheel **440** carried by the body **100**. One edge following sensor **310** and grass character sensor **320** pair is carried by the body **100** and located forward of the fore grass comber **510**, aligned parallel to a center axis **105**, and laterally in-line with each other. A second edge following sensor **310** is carried by the body **100** and located rearward of the fore grass comber **510**, but forward of the cutter **200**A.

Referring to FIG. **2**B, a robot **12** includes a body **100** carrying two leading flattener wheels **440** located forward of an edge following sensor **310** and a cutter **200**A that extends to a cut side **102** edge of the robot **12**. The edge following sensor **310** is located rearward of a fore grass comber **510** carried by the body **100**, but forward of the cutter **200**A. A grass character sensor **320** is carried by the body **100** and located forward of the fore grass comber **510**. In this example, the edge following sensor **310** is not laterally in-line with the grass character sensors **320**. A trimmer **220** is carried by the body **100** on a different side from the edge sensor **310** and/or cutter **200**A. One of the leading flattener wheels **440** (e.g. casters) may depress the grass ahead of a cut-portion span **312** of the edge sensor **310**, or immediately ahead of it (e.g., separated in the moving direction by less than a cut grass height or about two inches).

Referring to FIG. **2**C, a robot **13** includes a body **100** having a substantially pentagonal shape of constant width in which the widest portion leads a center line **105**, with a drive differential substantially on the center axis **105** connecting left and right drive wheels **410** and **420** respectively. A leading caster **440** and a trailing caster **430** are each carried by the body **100**. Three reciprocal cutters **200**B are disposed on the body **100** at different front-to-back locations that overlap serially in cut width. An extended one-piece grass sensor array **315** is located forward of a fore grass comber

510 and includes edge following sensors 310 and grass character sensors 320. A trimmer 220 may be coupled to the body 100 either of the uncut or cut sides, 101 and 102 respectively. A drive wheel 420 may depress the grass in a narrow portion following the cut-portion span 312 of the cut edge sensor 310 (i.e., no grass comber follows at least this wheel).

FIG. 3A is a schematic diagram illustrating another exemplary lawn care robot 14 having a substantially circular shape. The body 100 carries differential drive wheels, 410 and 420 respectively, substantially on the center axis 105, one leading caster 430, and three different rotating multi-"exacto" Bellinger blade cutters 200B (as used in U.S. Pat. No. 3,550,714, although with a guard to cover the blades when the cutter 200B is not rotating, and optionally powered by separate motors). The three rotary cutters 200B are placed at different front-to-back locations with overlapping cut widths. The arrangement of the cutters 200B shown (i.e., diagonally) is amenable for either reciprocal cutters 200A or rotating cutters 200B, or counter rotational shear. An edge following sensor 310 disposed on the body 100 includes a fore edge sensor bank 3102 preceding an aft edge sensor bank 3104 in the direction of cutting to provide auxiliary positional input for determining whether the robot 14 is proceeding linearly. For example, if the fore cut edge sensor 3102 and the trailing edge sensor 3104 are aligned along a single line parallel to the forward direction of travel of the robot 14 and both indicate the presence of the cut edge 26, the robot 14 may determine that it is traveling substantially linearly. However, if only one of the cut edge sensors 3102, 3104 indicates the presence of the cut edge 26, the robot 14 may have deviated from a straight line path. More complex interpretation and error-detection is also possible. The leading sensor 3102 may be wider or narrower than the trailing sensor 3104 and is optionally placed on an extending or extended arm 3106 as shown. A trimmer 220 may be coupled to the body 100 either of the uncut or cut sides, 101 and 102 respectively. The fore grass combers 510 may be replaced with fan blades for drawing up the grass with air flow concentric with the rotating cutters 200B.

FIG. 3B is a schematic diagram illustrating a layout of another exemplary lawn care robot 15 having a rectangular shape. The robot 15 includes a body 100 carrying differentially steered drive wheels 410 and 420, respectively, located near rear corners of the body 100, and two leading casters 430, located near forward corners of the body 100. Differential steering allows fast yaw rates. Wheels 410,420,430 located at the corners of the rectangular body 100 allows for good approach/departure angles and stability. The robot 15 also includes a cutter 200, a battery 160, edge detectors 310, calibrators 320, and boundary detectors 1500, all carried by the body 100. Front and rear bumpers 110A and 110B, respectively, are secured to the body 100 and may be configured to detect contact. Tight spacing between the wheels 410,420,430 and the cutter 200 allow for reasonable anti scalping. The turning center 150 is located between the drive wheels 410 and 420, respectively. The component layout and body configuration allow the robot 15 to cut up to boundaries and walls and is likely more efficient than a skid steer configuration (shown in FIG. 3D), but may have difficulty cutting to a 90 degree edge. The robot 15 is less likely to damage turf 20 while turning. Drawbacks to the component layout and body configuration of the robot 15, as shown, include not being able to turn in place, requiring bumper protection for all areas for and aft of the drive wheels 410 and 420, respectively, and needing slightly less than 2 times its length to turn 360 degrees (48"-60"). The robot 15 is stable, but transfers about 20% of its weight fore and aft as well as left and right at about 30 degree slopes, which causes difficulty or inability to navigate 30 degree slopes in reverse due to traction loss and drift. A forward center of gravity creates enough inertia to generate wheel slip in wet grass on flat terrain during edge following. The traction loss results in a change in robot heading or drift, which may affect edge following even on flat terrain.

FIG. 3C is a schematic diagram illustrating a layout of another exemplary lawn care robot 16 having a shape of substantially constant width. The robot 16 includes a body 100 carrying differentially steered drive wheels 410 and 420, respectively, located near rear corners of the body 100, and a leading caster 430, located on a forward portion of the body 100. The robot 16 also includes a cutter 200, a battery 160, edge detectors 310, calibrators 320, and boundary detectors 1500, all carried by the body 100. Front and rear bumpers 110A and 110B, respectively, are secured to the body 100 and may be configured to detect contact. Tight spacing between the wheels 410,420,430 and the cutter 200 allow for reasonable anti scalping. The turning center 150 is located between the drive wheels 410 and 420, respectively. The component layout and body configuration allow the robot 15 to cut up to boundaries and walls as well as cut to a 90 degree edge. The robot 15 is not likely to damage turf 20 while turning. The robot 15 is stable, but transfers about 20% of its weight fore and aft as well as left and right at about 30 degree slopes, which causes difficulty or inability to navigate 30 degree slopes in reverse due to traction loss and drift. A forward center of gravity creates enough inertia to generate wheel slip in wet grass on flat terrain during edge following. The traction loss results in a change in robot heading or drift, which may affect edge following even on flat terrain.

FIG. 3D is a schematic diagram illustrating a layout of another exemplary lawn care robot 17 with skid steering. The robot 17 includes a body 100 carrying differentially steered left and right drive wheels 410 and 420, respectively, located near front and rear corners of the body 100. To turn, the robot 17 may lock one or more wheels 410,420 while driving the others. The robot 17 also includes a cutter 200, a battery 160, edge detectors 310, calibrators 320, and boundary detectors 1500, all carried by the body 100. Front and rear bumpers 110A and 110B, respectively, are secured to the body 100 and may be configured to detect contact. Tight spacing between the wheels 410,420,430 and the cutter 200 allow for reasonable anti scalping. The turning center 150 is located substantially near the center of the robot 17. The component layout and body configuration allow the robot 17 to cut up to boundaries and walls, but may have difficulty cutting to a 90 degree edge. The robot 17 can turn on its center. Four wheel drive reduces the need for a low center of gravity and offers excellent step and hill climbing ability. A 50-50 weight distribution limits the occurrence of drift on slopes.

FIGS. 3E-H are block diagrams depicting typical control electronics and instrumentation which may apply to any appropriately similar robot described herein. FIGS. 3E and 3F are block diagrams suitable for a robot 10 with differential steering and an oblong "tombstone" form. Essentially the same components may be used in any of the differentially steered robots disclosed herein. As shown in FIGS. 3E and 3F, a bumper 110 is connected to left and right bump sensors 110L and 110R, respectively, at each of front and rear ends. These permit the robot 10 to detect the direction of a bump using the timing of actuation (e.g., if the left front is actuated before the right, an obstacle is forward and to the

left). The controller **450** in main electronics **5400** can use this direction to back and turn the robot **10** away and angled away from the side of detection. Hard surface detectors **330**E as discussed herein (one method of determining a lack of grass) are placed at all four corners of the robot **10** and monitored by the controller **450**. Artificial boundary (VF—Virtual Fence) detectors **529** as disclosed herein are also placed at all four corners of the robot, monitored by the controller **450**. Wheel drop sensors **430**A are part of the wheel assemblies of caster **430** and left and right drive wheels **410** and **420**, respectively, monitored by the controller **450**. Detections on bump, wheel drop **462**A, hard surface **330**, and VF boundary **529** sensors are activating conditions for obstacle avoidance behaviors and/or obstacle following behaviors ("behaviors" in the context of behavior based robotics) as disclosed in U.S. Pat. No. 6,809,490, as well as those behaviors disclosed in U.S. Patent Application No. 20070016328 for "Autonomous surface cleaning robot for wet and dry cleaning" to Ziegler et al., herein incorporated by reference in its entirety.

FIGS. **3**E and **3**F further show encoders **430**B provided to each wheel assembly **410**, **420**, **430**, which are monitored together with bumps and motor currents by the controller **450** to register a stuck condition (stasis), an activating condition for escape behaviors as disclosed in U.S. Pat. No. 6,809,490. Similarly, a cutter motor assembly **202** is provided with an encoder for detecting jams and speed. Right and left cut edge sensors **310** as described herein in various forms (**310**A, **310**B . . . **310**X) are provided and employed by the controller **450** as described herein. A wireless transceiver **55** communicates with the controller **450** (interchangeably controller **5400**) to permit the wireless remote to send and/or receive signals. A user interface **5410** (e.g., display panel and/or buttons) controlled from the controller **450** permits status signals and instructions. A manual mode interface **5411** is as described herein with reference to mounting, dismounting, and folding handles (e.g., permitting dead man and other signals to be switched, and handle status detected), for manual and autonomous modes.

FIGS. **3**E and **3**F differ primarily in that FIG. **3**E is primarily powered by an internal combustion engine **5451** (which may directly drive some components via clutches and/or transmissions, and may also drive an alternator or generator for powering devices or charging a battery **5454** to do the same). FIG. **3**F is primarily powered by a battery **5501** (which powers, e.g., brushless or other DC motors via motor control circuits and motor amplifiers). An internal combustion engine is primarily selected for energy density and rapid cycle times (e.g., replacing fuel is faster than recharging a battery), and need not be used to directly drive a cutter **200**.

It should be noted that a feature of the both internal combustion and battery powered arrangements is that when the robot **10** is placed in manual mode, clutches on the driven wheels (in some instances not shown, but all driven wheels disclosed herein may be clutched for this purpose) disengage wheels that are driven in autonomous modes, providing more power for manual mode. In each case, the controller **450** may, in response to the detection of manual mode (optionally in association with the handle being attached or unfolded), activate a high power mode for the cutter **200** (the cutter motor, gearbox, clutch, and cutting element strength being selected to accommodate this greater stress mode). This is appropriate for instances in which the user believes or perceives the robot **10** may be overmatched by lawn growth. An additional feature is that the wireless transceiver **55** may be used to activate a "normally off" switch connected to the ignition of an IC motor or motor current loop on an electric motor. When the robot **10** is out of range or unable to receive wireless signals from of a wireless remote that broadcasts a (continuous or interval of seconds to minutes) dead man signal, the robot **10** will be deactivated—and may be remotely deactivated by stopping the dead man signal.

The battery powered robot **10** of FIG. **3**F is controlled as discussed herein with respect to the included schematics and control diagrams. The internal combustion motor robot **10** of FIG. **3**E includes engine monitoring and control (ECU) **5402** for monitoring the state of the motor **5451**. Various sensors, including voltage and current states as well as conventional sensor configurations, may be connected to the ECU **5402**, including some or all of intake air pressure and temperature, barometric air pressure, coolant temperature, throttle position, crank position, cam position, fuel injection start angle and pulse width, and spark advance. Fuel level, ignition status, kill switch status, and dead-man switch status may be monitored by the ECU **5402** or main controller **450** or **5400**. The motor **5451** powers a generator **5452**, via a conventional gearbox or other transmission. If the gearbox is fully back-driveable or with appropriate gear ratios, the generator or alternator **5452** may be configured to act as a starter motor (with appropriate circuitry). Power conditioning **5404** turns the output of the generator **5452** into smoothed, less noisy, and optionally DC current for charging batteries and driving electric motors. The battery **5454** may be connected for electric start of the IC motor **5451** for powering electric motors in left wheel assembly **410**, right wheel assembly **420** (if these are not directly driven), and for powering main electronics **5400** and wireless transceiver **55**. Dead man signals or switches (normally off), or kill switches (normally on) as described herein are connected to leave the main electronics **5400** and wireless transceiver **55** powered even when the robot **10** is immobilized or unable to cut by disabling ignition, fuel supply, air supply, normally disengaged or normally engaged clutches, or motor current loops. The internal combustion motor robot **10** of FIG. **3**E includes a clutch **5453** and corresponding actuator (e.g., solenoid, motor, or EM) intermediate the IC motor and the cutter **200** itself. The clutch **5453** disengages the IC motor from a mechanically powered (via a transmission such as a belt, shaft, chain, or gearbox) cutter **200**, or disengages an electric motor (not shown) from an electrically powered (via the generator **5452**) cutter **200**.

FIGS. **3**G and **3**H are block diagrams depicting typical control electronics and instrumentation which may apply to any appropriately similar robot described herein, but are particularly suited for an articulating "skidder" configuration. Those elements that have like numbers as elements in FIGS. **3**E and **3**F have substantially the same structure and function.

Contrasting FIG. **3**F to FIG. **3**H, the skidder or pivoting configuration (rather than having a single forward caster) includes left and right passive wheel assemblies **5210**. Each of these includes a drop sensor **430**A and encoder **430**B monitored by the controller **450** or main electronics **5400**. An articulating pivot **5305** as described herein separates the body **5000** into two parts. The pivot **5305** includes a slip ring or flexible wire harness for passing wiring from the first portion **5100** to the second portion **5200** of the body **5000**. A (preferably electric motor) pivot actuator **5310** is controlled by main electronics **5400**, and the pivot **5310** position is monitored by an absolute encoder (i.e., one which returns an absolute position rather than relative position). A main drive wheel **5110** is powered by a motor assembly **5455**.

Many of these same differences are found in contrasting the IC configuration of FIG. **3**E to the IC skidder configuration of FIG. **3**G. The IC skidder configuration as shown includes two clutch configurations. A drive clutch actuator and clutch **5452** disengages the IC motor **5451** from a mechanically powered (via a transmission such as a belt, shaft, chain, or gearbox) main drive wheel **5110** or disengages an electric motor (not shown) from an electrically powered (via the generator **5452**) main drive wheel **5110**. A cutter clutch actuator and clutch **201** disengages the IC motor **5451** from a mechanically powered (via a transmission such as a belt, shaft, chain, or gearbox) cutter **200**, or disengages an electric motor (not shown) from an electrically powered (via the generator **5452**) cutter **200**. These and other clutches disclosed herein may be engaged or disengaged for manual mode in stability situations (e.g., using a tilt sensor the controller determines that the robot should be immobilized and engages clutches appropriately) or when an E-stop, dead-man switch or signal, or kill switch or signal is used. The controller **450** may also engage and disengage clutches during escape behaviors.

FIG. **3**I depicts connections between electronic components and is one way of connecting components as set forth in FIG. **3**G and herein below. FIG. **3**I is different from FIG. **3**G at least in that all of the motors for drive, pivot, and cutting are electric; and that the two front wheels are each driven. Steering motors **5456** on left and right forward sides are connected (including motor control and amplification) to the control board **5400**. An articulation (pivot) motor **5310**, a main drive motor **5455**, and a payload or cutter motor **202** are similarly connected (including motor control and amplification). Power conditioning **5404** includes a charging or recharging circuit for the battery (one or two circuits may convert IC motor/alternator AC and/or household AC to charge the battery), conditioning for the IC motor/alternator AC current to smooth and remove noise using inductors or the like, and a starting circuit for providing starting current (in appropriate AC or DC form, voltage, and current) to the starter and/or alternator. The starter and alternator may be the same or different devices. Both a kill switch K and a dead man switch D intervene between the ignition and the IC motor **5451** (e.g., in a manner to damp or short ignition functions). Each can be activated by the control board **5400** and robot behaviors and also directly by manual switches, relays, or the like provided on the robot body or attachable/foldable handle.

FIGS. **3**J and **3**K show block component layouts of some of the components discussed with reference to FIGS. **3**G and **4**A-N below. Payload and payload motor **202** are usually near the ground (in order to carry out lawn care), shown in the middle of the robot. Steering and articulation motors (electrical) **5456** and **5310** are placed essentially adjacent the wheels or pivot to be controlled. However, as shown in FIGS. **3**J and **3**K, at least half (three components of, in this case, six components) of the heaviest components that may be placed in different locations—an IC engine **5451**, alternator/generator **5452**, drive motor **5455**, battery **5454**, control electronics board **5400** (if more than one board, the heaviest ones of these), and fuel tank **5458**—are positioned at least in part below the center axis of the highest diameter driven wheel (here main drive wheel **5110**) in order to lower the center of gravity. It is not necessary for these components to be placed within the volume of the highest diameter driven wheel **5110** in order to be below the center axis of it. However, as shown in FIGS. **3**J and **3**K, it is preferable to place at least half of these six components within the volume of the highest diameter driven wheel. In FIG. **3**J, the IC engine **5451**, alternator **5452**, drive motor **5455**, battery **5454**, and fuel **5458** are within the volume of the highest diameter driven wheel and the control electronics board **5400** is placed within the main body but outside the volume of the highest diameter driven wheel. In FIG. **3**K, the control electronics board **5400**, drive motor **5455**, and battery **5454** are within the volume of the highest diameter driven wheel, but the IC engine **5451**, alternator **5452**, and fuel **5458** tank are placed within the main body but outside the volume of the highest diameter driven wheel. Heavy components (often the engine, motors/generators, batteries, fuel, control electronics including motor amplifiers) are used to lower the center of gravity.

Referring to FIGS. **4**A-N, a robot **18** includes a body **5000** having first and second portions **5100** and **5200**, respectively, joined at an articulated joint **5300**. The first body portion **5100** defines a payload area **5102** that carries a controller **5400**, a drive motor **5450**, and a power source **5500**, for example. At least one drive wheel **5110** rotates about an axis **5105** defined by the first body portion **5100**. The outer diameter of the drive wheel **5110** is sized to be greater than a length and height of the payload area **5102**. In some examples, the outer diameter of the drive wheel **5110** is about 16 inches. In one example, as shown in FIGS. **4**A-D, one drive wheel **5110** defines an inner cavity housing the payload area **5102**. The first body portion **5100** includes left and right arms **5120** and **5130**, respectively, extending from the payload area **5102** around the at least one drive wheel **5110** to the articulated joint **5300**. The second body portion **5200** defines an axis **5205** and carries at least one free wheel **5210** that rotates about rear axis **5205**. In some examples, the outer diameter of the free wheel **5210** is about 9 inches and the robot **18** has a center of gravity CG a height H from a ground surface of about 3 inches. The at least one free wheel **5210** may pivot about an axis perpendicular to the rear axis **5205**. For example, the at least one free wheel **5210** may pivot laterally with the pivot axis parallel to a direction of travel, allowing the second body portion **5200** to lean into turns.

The articulated joint **5300** includes an actuator **5310** (e.g. a motor and gearbox) controlled by the controller **5400** and configured to rotate the first and second body portions **5100** and **5200**, respectively, in relation to each other about at least one pivot **5305** of the articulated joint **5300**. In some examples, as shown in FIG. **4**B, the articulated joint **5300** allows the second body portion **5200** to twist relative to the first body portion **5100** about a drive direction. In some examples, as shown in FIG. **4**D, the articulated joint **5300** rotates a drive direction of the first body portion **5100** an angle A of between about +90° and about −90° with respect to a drive direction of the second body portion **5200**. This allows the robot **18** to pivot 360° about a free wheel **5210**.

FIGS. **4**E-G illustrate an example of robot **18** with two drive wheels **5110** carried by the first body portion **5100**. The configuration shown partially exposes the payload area **5102** between the two drive wheels **5110**. The two drive wheels **5110** may be driven independently from each other.

Referring to FIGS. **4**H-I, the robot **18** may be driven with the first body portion **5100** leading the second body portion **5200** and vice-versa. The robot **18** includes at least one lawn care unit **5600** carried by the first and second body portions **5100** and **5200**, respectively. In the example shown, the robot **18** includes lawn care units **5600**A and **5600**B carried by the first body portion **5100** and lawn care unit **5600**C carried by the second body portion **5200**. When the robot **18** is configured to have the first body portion **5100** leading the second body portion **5200**, lawn care unit **5600**A may be

configured as a cutter **200**, lawn care unit **5600**B may be configured as a grass comber **510**, **520** and/or a cut edge detector **310**, and lawn care unit **5600**B may be configured as a cutter **200**. When the robot **18** is configured to have the second body portion **5200** leading the first body portion **5100**, lawn care unit **5600**A may be configured as a cutter **200**, lawn care unit **5600**B may be configured as a cut edge detector **310**, and lawn care unit **5600**B may be configured as a grass comber **510**, **520** and/or a cut edge detector **310**.

Referring to FIGS. **4**J-N, in some examples, the drive wheel **5110** is supported by the first body portion **5100** on three roller supports **5112**, each positioned about 120° from the other. A drive pinion **5114** coupled to a motor **5450** by a transmission **5455** drives the drive wheel **5110**. The drive wheel **5110** has a relatively low center of gravity CG-W. In some instances, the drive wheel **5110** defines a stepped profile, as shown in FIG. **4**K. In other instances, the drive wheel **5110** defines a truncated profile with a sharp peak, as shown in FIG. **4**L. In other instances, the drive wheel **5110** defines a knobbed profile, as shown in FIG. **4**M. In other instances, the drive wheel **5110** defines a treaded and/or curved profile, as shown in FIG. **4**N.

Referring to FIGS. **5**A-B, a rotary cutter **2000** includes upper and lower disk guards **2010** and **2012**, respectively, and first and second cutter blades **2013** and **2014**, respectively, disposed between the upper and lower disk guards **2010** and **2012**, respectively. The rotary cutter **2000**, in some examples, includes first and second blade tip guard combs **2015** and **2016**, respectively, disposed on corresponding the first and second cutter blades **2013** and **2014**, respectively. The blade tip guard combs **2015**, **2016** reduce blade injuries and comb the grass **20**. An optional blade lock **2017** holds the first and second cutter blades **2013** and **2014**, respectively, together to form one rotating cutter.

In some implementations, the robot **10** includes an aerator or erector which lifts cut grass **24**, thereby adding perceived volume to the mowed lawn **24** and enhancing an aesthetic appearance of the lawn **20**. The aerator/erector may include an active brush or comb for brushing the grass upward, for example. The robot **10** may include an aeration and/or lift system as disclosed in U.S. Pat. No. 6,611,738; US Patent Application Publication 2004/0187457; and/or U.S. Pat. No. 3,385,041, all incorporated herein by reference in their entireties.

In some instances, the surface treater **200** includes sheep shear-style or hedge-trimmer-style cutters **200**A, which confine their cutting action to a particular radius and prevent objects greater than that radius from being accidentally cut. For example, the size of the cutting radius may be selected to be smaller than a child's fingers or toes, so as to prevent accidental injury. Moreover, the cutter **200** cuts with a substantially low energy rate of approximately 70 watts over a 0.5 meter cutting length. The rate of energy expenditure is low enough that the robot **10** can run for a sufficient period of time to cut a yard of typical size.

FIG. **5**C is a schematic view of a simplified reciprocating cutter **2050** as an example of a reciprocating cutter **200**A. The sickle-bar cutter **2050** includes first and second blades, **2051** and **2052** respectively, positioned parallel to each other and moved in opposite reciprocating motions by an actuator **2060**.

Referring to FIGS. **5**D-E, a reciprocating cutter **2050** includes a housing **2055** carrying an arm **2070** positioned to rotate horizontally (e.g. from right to left and back) with regard to the lawn about a pivot bearing **2072**. A cutting blade **2080** is mounted to an external end of the arm **2070** and abuts a comb **2084** connected to the housing **2055**. The spinning motion of a driven shaft **2076** is translated into reciprocating side-to-side motion for the arm **2070** via the eccentric bearing **2074**. As the arm **2070** moves horizontally from side to side, the teeth **2082** of the cutting blade **2080** shearingly slide horizontally while in contact with the tines **2086** of the comb **2084**, cutting any blades of grass caught in grooves **2085** formed between the adjacent cutting blade **2080** and comb **2084**. In one example, the distance of reciprocation is five centimeters or less (i.e., of the blade **2080** with respect to the comb **2084**).

Referring to FIG. **5**F, the reciprocating cutter **2050** includes a blade tensioner **2090** providing evenly-spaced downward tension on the cutting blade **2080**. The teeth **2082** of the cutting blade **2080** are even urged against the comb **2084**, enhancing the shearing action. The blade tensioner **2090** may include one or more arched extensions extending from the arm **2070**. Alternatively, the blade tensioner **2090** may include a separate unit connected to the body **100**, such as a heavy horizontally-aligned bar that provides a downward pressure against the cutting blade **2080**.

Referring to FIG. **5**G, the reciprocating cutter **2050** includes two cutting blades **2080**A and **2080**B, each actuated by separate arms **2070**A and **2070**B, respectively, reducing the number of teeth **284**A, **284**B on each cutting blade **2080**A and **2080**B, respectively.

The cutting blade **2080** may include four teeth **2082** per every five comb tines **2086**. Alternatively, the cutting blade **2080** may include nine teeth **2084** per every ten tines **2086**. The cutting blade **2080** and comb **2084** may function such that only one (or alternatively, two) teeth **2082** are cutting at a time during operation of the cutter **2050**. The teeth **2082** of the cutting blade **2080** and the tines **2086** of the comb **2084** may have mutually different pitches and may be chamfered. The number of teeth **2082** or tines **2086** may be a multiple of the number of teeth present in a typical sheep-shearer; for example, three times the factor of widening of the comb **2084** with respect to the sheep-shearer. The clamping force provided to the blade **2080** against the comb **2084** may be uniform, or may vary across the horizontal area of the blade **2080**, within a range of acceptable clamping force. The material of the cutting blade **2080** and/or comb **2084** may include hardened metal (such as steel) which is stamped, molded, then machined, forged, and machined again.

The comb **2080** and/or cutting blade **2084** may include mounting holes for mounting the cutting blade **2080** or comb **2084** to a yoke. The teeth **2082** or tines **2086** may have rounded tips to guide blades of grass into the grooves **2085**. The spacing of the teeth **2082** or tines **2086** may be established to optimize the opening gap **2085**.

The curves of the blade **2080** and comb **2084** may have outlines similar to those of a sheep-shearing device when the radius is nine inches or less; when the radius of curvature thereof is greater than nine inches, the curves of the blade **2080** and comb **2084** may be altered in accordance with the driving radius and cutter radius.

Referring to FIG. **5**H, a cutter **2100** includes a first blade **2110** mounted to and rotatably driven by a motor **2140**. A second blade **2110** is mounted to and rotatably driven by a planetary gearbox **2130** driven by the motor **2140**. The first and second blades **2110** and **2120**, respectively, rotate in opposite directions to shear grass. The cutter **2100** has the lift capabilities of a conventional rotary cutter, but requires less power to operate and generally provides a cleaner cut. In some examples, the second blade **2110** is either fixed or free floating, rather than driven by a planetary gearbox **2130**.

In the fixed second blade configuration, only the first blade **2110** rotates thereby shearing grass with a scissor type action.

Referring to FIG. **5**I, a cutter **2200** includes a cutter frame **2210** defining a longitudinal axis **2215**. The cutter frame **2210** is mounted to the body with the longitudinal axis **2215** substantially parallel to a ground surface. A driven wire holder **2220** is rotatably mounted to the cutter frame **2210** to rotate about the longitudinal axis **2215**. The wire holder **2220** includes a plurality of spaced disks **2222** and at least one wire **2224** secured near a peripheral edge of the disks **2222** and arranged substantially parallel to the longitudinal axis **2215**. The rotating wire holder **2220** and associated wire(s) **2224** cuts grass with relatively less power than a conventional rotary cutter.

In some examples, the surface treater **200** includes a fertilizer or pesticide dispenser for distributing fertilizer or pesticide over the yard **20**, either in lieu of or in addition to other lawn care tasks such as mowing.

Referring to FIGS. **6**A-B, the robot **10** generates electrical power which may be stored. One implementation utilizes a generator **1702**, such as a dc motor that spins to generate DC current. Control often involves a voltage regulator **1704** to prevent high and low voltages in the system. Another implementation includes an alternator. An alternator is a three phase generator that is run through a set of diodes to rectify the AC current to DC. With the use of an additional voltage regulator it is possible to get stable, nearly ripple-free DC current from the alternator.

FIG. **6**A illustrates a hybrid mechanical-electric system **1700**A including a fuel source **1702** delivery fuel to an engine **1704** that drives a cutter **1706** and a generator **1708**. The generator **1708** is connected to a voltage regulator **1710**. The voltage regulator **1710** is connected to an energy storage unit **1712** (e.g. a battery), a drive motor **1714** and electronics **1716**.

FIG. **6**B illustrates an all electric system **1700**B including a fuel source **1702** delivery fuel to an engine **1704** that drives a generator **1708**. The generator **1708** is connected to a voltage regulator **1710**. The voltage regulator **1710** is connected to an energy storage unit **1712** (e.g. a battery), a drive motor **1714**, a cutter **1706**, and electronics **1716**.

Referring to FIGS. **6**C-D, the robot **10** includes six different categories of components; each of which performs a narrow function of total system operation. The six categories include: C1) Fuel—Storage and delivery of fuel to the engine; C2) Intake—Passage of air into the engine; C3) Engine—Combustion of fuel to create mechanical work from stored energy; C4) Electrical Output—Components to create usable electrical power from shaft work; C5) Starting—Components to start the engine; and C6) Mechanical Output—Components designed to channel shaft work to appropriate locations. For each of the six categories, there are three separate types of components: required (minimum complexity (cost) path to operation), optional (these components will add additional features or functionality to the product at additional cost, and expected.

FIG. **6**E provides a schematic view a neighborhood **1000** including houses **1002**, grass-cutting obstacles **1004** (e.g. trees **1004**A, bushes **1004**B, and water **1004**C), boundaries **1006** (e.g. fences **1006**A and property lines **1006**B), non-cuttable areas **1008** (e.g. driveways **1008**A, sidewalks **1008**B, and roads **1008**C), and cuttable areas **1020**. Although a fairly simple neighborhood **1000** is shown, the depiction is sufficient for substantially topologically equivalent, less linearly oriented lawns, or lawns with islands, multi-section lawns, and or other discontinuities.

The delineation between areas intended to be traversed by the robot **10** and areas not intended to be traversed by the robot **10** may be divided into different types of boundaries, including visible boundaries and invisible boundaries, natural boundaries, artificial boundaries, arbitrary, political boundaries, navigable and blocking boundaries. Lawn edges are a type of arbitrary boundary that abut many kinds of non-grass or non-mowable areas (e.g., fences, flowerbeds, gardens, mulch, sidewalks, walls, steps). Arbitrary boundaries also include boundaries established for property or other reasons within a physically mowable continuous grass area. Examples of arbitrary boundaries include a boundary between a bed of azaleas (bedded in tree-bark mulch) and a grassy lawn and a boundary between a grassy lawn and a concrete driveway. The transition between the grass and non-grass area, or the non-grass area itself, is discernable by virtue of differing physical properties. In many cases, the difference is visually discernable. However, the robot **10** uses a limited set of less complex physical characteristics, such as average reflected wavelengths of light (i.e., color) or mowing resistance (correlating to grass presence).

The arbitrary boundaries which are not readily ascertainable by differences in physical characteristics include property lines **1006**B between adjacent lots in a neighborhood **1000** and a border between a first yard region **1020** which should be mowed and a second yard region **1020** which should not be mowed due to seeding, damage, or the like. To recognize the arbitrary boundaries, the robot **10** uses boundary responders **600**, such as lengths of identifiable cord ("cord" also meaning wire, tape, chain, or cord of discrete elements in a bounded line).

FIGS. **7**A-**7**E depict structures relevant to switching between autonomous and manual operation of the robot **10**. FIGS. **7**A, **7**C-**7**F depict structures suitable as an analog of a conventional push mower handle.

FIGS. **7**A and **7**B are schematic views of methods of navigating a lawn care robot **10**. Referring to FIG. **7**A, one method of manually leading the robot **10** includes using an IR or wireless remote **50** that sends a signal to a receiver **55** on the robot **10**. The drive system **400** is configured to follow the signal received from the remote **50**

Another method includes guiding the robot **10** with a push bar **116** attached to the body **100**. The push bar **116** may be detachable from or stowable on the body or housing **100**. For example, if the robot **10** is programmed to avoid thick vegetation so as not to become mired or entangled, an operator may nonetheless override the behavior by guiding the robot **10** with the push bar **116**. In some cases, the push bar **116** includes a switch, speed setting, or joystick to advance and steer the robot **10**. In one instance, the push bar **116** includes one or more pressure or strain sensors, monitored by the robot **10** to move or steer in a direction of pressure (e.g., two sensors monitoring left-right pressure or bar displacement to turn the robot **10**). In another instance, the push bar **116** includes a dead man or kill switch **117**A in communication with the drive system **400** to turn off the robot **10**. The switch **117**A may be configured as a dead man switch to turn off the robot **10** when a user of the push bar **116** ceases use or no longer maintains contact with the push bar **116**. The switch **117**A may be configured act as a kill switch when the push bar **116** is stowed, allowing a user to turn off the robot **10**. The dead man or kill switch **117**A may include a capacitive sensor or a lever bar. In another instance, the push bar **116** includes a clutch **117**B to engage/disengage the drive system **400**. The robotic mower **10** may be capable of operating at a faster speed while manually operated by the push bar **116**. For example, the robotic

mower **10** may operate at an autonomous speed of about 0.5 msec and a manual speed greeter than 0.5 msec (including a "turbo" speed actuatable to 120-150% of normal speed).

Referring to FIG. **7**B, in yet another method of navigating the robot **10**, the robot **10** includes a pull leash or retractable lead wire **118** fed through a guide **120** from a spool **122**. In this example, the drive system **400** includes a controller **450** carried by the body **100** and controlling the release and retraction of the spool **122**. The pull wire extends for 6-10 feet, for example, and the robot **10** monitors the amount of extension directly or indirectly (encoder, etc.), as well as the direction in which the wire is pulled (monitoring a position of the wire guide **120**). The robot **10** follows the direction of the pull and controls speed to maintain a wire length. FIG. **7**B also shows a grass erector **510** carried by the body **100** forward of the cutter **200**. The grass erector **510**,**520** includes a driven wheel **510**A having an axis of rotation parallel to the lawn **20**,**1020** and a plurality of flexible grass agitators **510**B extending radially outward from the wheel **510**A.

Referring to FIGS. **7**C and **7**D, robot **19** is configured for autonomous and manual (push) modes. As shown in FIG. **7**D, the handle **116** is configured substantially in the form of a conventional push mower handle. The handle **116** includes, at an upper end, a dead man switch **117**A manually operable by the hand of an operator. The dead man switch **117**A is connected to a spring loaded actuator **117**D and is thereafter connected to the robot **19** using a connection line **117**E (which may be a movable mechanical actuator cable or an electrical line). At a lower end of the handle **116**, the connection line **117**E is passed through a connector **116**C to the robot **19**. The handle **116** is connectable to the robot **19** via the connector **116**C, as well as via a brace **116**B. The lower end of the handle **116** is connected substantially in the neighborhood of the axis of the wheels **410**,**420** at the rear of the robot **19**, while the brace **116**B and lower connection together permit the robot **19** to be tipped via the handle **116** as the handle is lowered by a user. In this manner, the robot **19**, used in manual mode, may be tipped and turned in place in the manner of an ordinary push mower.

The dead man switch **117***a* is provided with a mechanical bias or spring that biases the switch **117***a* to an "off" position. In this case, "off" means a mechanical or electrical state in which an internal combustion or electrical cutter drive cannot function. For an internal combustion cutter drive, examples of "off" include an open circuit from an ignition or a short between a spark terminal and an engine block or other known device for disabling the IC engine. For an electrical cutter drive, examples of "off" include an open circuit, normally off relay, or other known device for disabling an electrical motor. In either case, a brake and/or clutch may be connected to the dead man switch **117***a* and actuated at the same time as, or instead of, disabling the motor. In an "on" position, the switch **117***a* is held against the bias of the spring by the operator. The switch **117***a* may not be locked or fixed in the "on" position.

The robot **19** depicted in FIGS. **7**C and **7**D, capable of receiving the detachable push/pull handle **116**, has an internal combustion engine (or equivalent fuel-based or combustion system providing high energy density such as fuel cells) for direct drive of a cutter, charging batteries or pressurizing fluids. The robot **19** also includes a number of electrical or hydraulic motors, including one or two drive motors **460** (driven to move the robot forward) and/or one or two steering motors **470** (driven at differential rates or together to turn the robot **10**). Each motor **460**,**470** that connects to a driven wheel is provided with an electromagnetic clutch or other electrically actuated clutch to disengage the respective motor in manual modes. One clutch may disengage more than one motor. The electromagnetic clutches may be controlled from the controller **450**, or more directly via the connector **116**C as discussed herein.

As shown in FIGS. **7**C and **7**D, the handle **116** is detachable via the connector **116**C provided to the robot and a corresponding connector **100**A provided on the robot body **100**. The connectors **116**A or **100**A may each be mechanical (i.e., if passing an actuating cable or transmitting its motion), or may be electrical (multi-pin connectors).

The connectors **116**A and **100**A may have additional functions. When the handle **116** is attached, the dead man switch **117**A is a normally off switch that transmits the "off" condition (disengaging or killing the cutter drive) to the mower via the connectors **116**A, and can be actuated manually to change to an "on" condition. However, upon removal of the handle **116** from the robot **19**, the normally "off" default condition is reversed in order to permit the robot **19** to operate autonomously (and restored whenever the handle **116** is attached). Either or both of the connectors **116**A, **100**A may be provided with a reversal switch that is actuated when the handle is removed, the reversal switch providing the same status as if the handle **116** were attached and the dead man switch **117**A held by an operator. While it is possible to carry out reversal switching in software, it is preferable that a dead man switch **117**A rely on robust mechanical connections or open/closed current loops to engage and disengage the switch **117**A. The reversal switch associated with connectors **116**A or **100**A also preferably employs a mechanical switch or open/closed current loop to provide the "switch on" condition. Alternatively, the reversal switch may be provided within the robot body **100** rather than directly at connectors **100**A, **116**A.

In some implementations, the connectors **116**A or **100**A, or the dead man switch **117**A, are monitored by a handle sensor that detects a presence or absence of the handle **116**. The handle sensor is connected to a controller **450**, which initiates or deactivates manual mode, (e.g., activating the clutches to disengage the drive and steering motors from the wheels) in response to a detected presence or absence of the handle **116**. Based on this detection, the controller **450** may prevent the robot **19** from entering any autonomous mode while the handle **116** is attached (with the exception of a set-up or testing mode in which the robot is pushed within detection range of active or passive barriers or responders.)

As shown in FIG. **7**C, as the robot **19** is used in fully autonomous modes, the handle **116** is left hanging or otherwise conveniently stored in a user's garage or other sheltered property. The robot **19** completes the bulk of the yard mowing, or all of the mowing in segmented areas. Depending on the yard configuration, uncut areas may be bounded by obstacles, otherwise unreachable, or outside a boundary set by the user. The user may choose to complete, finish, or touch up remaining areas. Preferably, the robot's dock, home base, or finishing location is in the vicinity of the handle storage location. In any case, the user mounts the handle **116** on the robot **19**. As the connectors **116**C and **100**A engage mechanically, the aforementioned reversal switch is deactivated, bringing the dead man switch **117**A into operation (and, as it is normally off, preventing cutting operations). The controller **450** of the robot **19** may detect the presence of the handle **116**A and enter a manual mode in response. Either implementation may be used by the controller **450** to power and disengage the clutches of the drive and/or steering motors, **460** and **470** respectively, so that the robot **19** may be freely pushed. In one example, the clutches are normally engaged so that a robot having a dead battery

or other power failure will not readily roll down a hill as the normally engaged clutches connect the non-backdriveable or backdriveable with resistance motors to the wheels **410**, **420**. The user may then freely push the mower, pressing the dead man switch **117**A to start the motor and/or cutters **200**. The robot **19** may be self-propelled in manual mode, faster than autonomous mode, and may be controlled using the dead man switch **117**A or other manual control.

FIGS. **7**E and **7**F depict robot **19** with a different, foldable handle structure and body structure, but in general similar to the detachable handle structure of FIG. **7**F. As shown in FIG. **7**F, the handle **116**, while in use, remains configured substantially in the form of a conventional push mower handle. The handle **116** includes a dead man switch **117**A with a spring loaded actuator **117**D and connects to the robot **19** via a connection line **117**E (not shown). The connection line **117**E is passed through a lower end of the handle **116** to the robot **19**. The handle **116** is connectable to the robot **19** via a pivot connector **100**A on the robot **19**, as well as via a sliding brace **116**B. The lower end of the handle **116** is connected substantially in the neighborhood of the axis of the wheels **410**,**420** at the rear of the robot **19**. The sliding brace **116**B and lower connection **100**A together permit the robot **19** to be tipped via the handle **116** as the handle **116** is lowered by a user. In this manner, the robot **19**, used in manual mode, may be tipped and turned in place in the manner of an ordinary push mower.

A folding joint **117**F or switches within the pivot connector **100**A or sliding brace **116**B may have the same functionality as the connectors **116**A and **100**A, previously described. When the handle **116** is unfolded the dead man switch **117**A is a normally off switch that transmits the "off" condition (disengaging or killing the cutter drive) to the mower via the pivot connector **100**A, and can be actuated manually to change to an "on" condition. However, upon folding of the handle **116** flush to the robot **19**, generally conforming to the body **100** of the robot **19**, the normally "off" default condition is reversed to permit the robot **19** to operate autonomously (and restored whenever the handle **116** is attached). The folding joint **117**F, the pivot connector **100**A, or sliding brace **116**B may be provided with a reversal switch that is actuated when the handle is folded down. The reversal switch provides the same status as if the handle **116** was unfolded and the dead man switch **117**A held by an operator. As shown in FIG. **7**E, the dead man switch **117**A may be folded down to a position in which it is facing up and substantially in the same position as a useful kill switch **117**C. In this position, and with the reversal switch activated, the dead man switch **117**A may become normally "on", actuatable to an "off" condition, and thereby also become a kill switch **117**C.

The mower in manual mode, with the handle attached and dead-man either on or off, may be used in a check setup mode by the user. This check setup mode would require the user to circumnavigate and approach all boundaries, obstacles, and marked guarded areas to be avoided by the robot. The robot, via the user interface, notifies the user upon the recognition or activation of each boundary, obstacle, or responder. The user would be instructed to diligently try and "fool" the robot (i.e., manually push the robot to test, avoid, and or approach areas not clearly bound by a boundary or responder) or escape boundary confinement without detection, and if successful, would know to place additional boundary segments or responders, including redundant boundary segments or responders as necessary. The robot may also be configured to permit autonomous mowing only after sufficient setup checking (e.g., certain distance odometered in check setup mode).

In some examples, the autonomous robot **10** includes a not-grass detector **330** to aid mowing grassy areas **20**, rather than areas which should not be mowed or traversed, such as concrete, mulched or gravel-covered surfaces. The not-grass detector **330**, in various examples, includes a mechanical, electrical, piezoelectric, acoustic, optical or other suitable sensor capable of detecting a presence of grass. Certain of the sensors discussed above with regard to the cut edge sensor **310** may function as the not-grass detector **330** if arranged in a position or extending to a position other than the location of the cut edge sensor. The not-grass detector **330** and cut edge sensor **310** may be integrated or combined as a single unit.

Referring to FIG. **8**A, in some implementations, a not-grass detector **330**A includes a chlorophyll detector having one or more light emitters **332** and an optical sensor **334**. The wavelengths emitted by the light emitters **332** are selected based on an absorption spectrum of chlorophyll. In one example, the not-grass detector **330**A includes four different colored narrow-spectrum light emitting diodes (LEDs) **332**A-D. LED **332**A emits a blue wavelength. LED **332**B emits a green wavelength. LED **332**C emits a yellow wavelength. LED **332**D emits a red wavelength.

The optical sensor **334** receives and analyzes light reflected from an area illuminated **20**A by the light emitters **332** to determine a presence of chlorophyll. In some examples, the optical sensor **334** includes a gray-scale or black and white (1 bit) detector. When an image provided by the optical sensor **334** is primarily dark or black (or weak signal) in response to blue and red light emitted by light emitters **332**A and **332**D, respectively, but is primarily light or white (or strong signal) in response to green and yellow light emitted by light emitters **332**B and **332**C, respectively, the robot **10** determines that the illuminated area **20**A likely includes grass and traverses and/or mows the illuminated area **20**A.

FIG. **8**B provides an example of signals from the optical sensor **334** (i.e., filtered averaged over the area **20**A) in response to four wavelength emissions, showing comparatively lower responses in the blue and red wavelengths, while comparatively higher responses in the green and yellow wavelengths. As depicted, the robot **10** encounters a non-green area while moving forward and then immediately backs up. As shown, the robot **10** may have encountered something red, but the signal of interest is the non-grass signal.

In additional implementations, a not-grass detector **330**B includes a plurality of light emitters **332** having different green wavelengths which are used for secondary color response tests, providing a lawn color range for further resolution. For example, the not-grass detector **330**B identifies green but not the same green as cuttable lawn areas **20**, **1020**. A lawn color may be characterized over time as the mower robot **10** covers the cuttable lawn area **20**, **1020**. Near IR, or UV black light LED's may also be used for the light emitters **332** in a similar manner. Polarization of the light emitted by the light emitters **332** (e.g. linear or circular) provides additional information.

In one example, gaff-like tape bearing unobtrusive detectable particulate or stranded media (e.g. iron filings, retro reflectors, or the like) is stuck onto a hard surface **1008**, such as a driveway **1008**A or sidewalk **1008**B, and removed, leaving the detectable media adhered to the surface **1008**.

The not-grass detector **330** detects the detectable media (e.g. light reflected off the detectable media).

In some implementations, the not-grass detector **330** also acts as a cliff detector, since it points down and is angled to focus on an area of interest. The absence of any signal is detection of a cliff.

Referring to FIG. **8**C, in some implementations, a not-grass detector **330**C includes an ultrasound or acoustic emitter **333** and a microphone or ultrasonic transducer **335** to record and measure acoustic reflections, e.g., echo attenuation, frequency shift or characteristics, to determine a grass presence grass. Hard surfaces **1008** (e.g. driveways **1008**A, sidewalks **1008**B, and roads **1008**C) reflect sound better than grass **20**, **1020**.

Referring to FIG. **8**D, a grass sensor **330**D includes a rolling idler wheel **336** (e.g. driven wheel) acoustically monitored by a microphone or piezoelectric pickup **335** for one or more characteristic frequencies, peaks, RMS amplitudes, and damping representative of non-cuttable areas **1008** (e.g. driveways **1008**A, sidewalks **1008**B, roads **1008**C, and flowers/garden **1008**D). In one example, the wheel **336** is turned in place to generate a rotational resistance characteristic of non-cuttable areas **1008**. In another example, the wheel **336** defines grooves **337** (e.g. longitudinally, laterally, diagonally, or sequentially some of each) that enhance acoustic and rolling resistance information. In another example, the robot **10** includes a pH or chemical sensor bare areas of dirt or pine needles.

Referring to FIG. **8**E, the grass sensor **330**, in some examples, includes an acoustic surface sensor **330**E having a sensor housing **3310** defining emitter and receiver receptacles **3313** and **3314**, respectively. An audio transmitter **3311** (e.g. a piezo-electric element, or moving coil and magnet assembly) is carried in the emitter receptacle **3313** and transmits an audio emission **3315** downwardly. A receiver **3312** (e.g. a piezo-electric element, or moving coil and magnet assembly) is carried in the receiver receptacle **3134** and is configured to receive a reflected audio emission **3316** off a ground surface **3340**. A controller **3350** monitors a received reflected audio emission **3316** and compares a maximum receive energy with a threshold energy to classify the surface as hard or soft. The audio transmitter **3311** transmits multiple audio emissions **3315**, each having successively larger wavelengths increased by half a fundamental frequency. In one example, the audio transmitter **3311** transmits a first audio emission **3315** at about 6.5 kHz (wavelength of about 52 mm) and a second audio emission **3315** at about 8.67 kHz. The step in transmission frequency between the first and second audio emissions **3315** changes the acoustic energy by a half of a wavelength of a fundamental frequency (e.g. by 26 mm). Small variations in a distance between the acoustic surface sensor **330**E and a target surface **3340** may cause large variations in receive energy due primarily to constructive and destructive interference.

In some examples, a relatively narrow band-pass amplifier **3362** limits external acoustic interference for reflected audio signals **3316** received by the receiver **3312**. A receive envelope detector **3364** receives a conditioned signal from the band-pass amplifier **3362**. The receive envelope detector **3364** is in communication with an A/D converter **3366**, which is in communication with the controller **3350**.

Using an audio transmitter **3311** and receiver **3312** separate from each other shortens a minimum sensing distance relative to a single unit transmitter-receiver. A single unit transmitter-receiver (e.g. in pulse-echo mode) generally has a wait period after a transmission for ringing to attenuate before the unit **330**E can listen for a reflected transmission **3316**.

Referring to FIG. **8**F, operation of the acoustic surface sensor **330**E commences by step S**100** of initializing a transmission frequency, step S**102** of initializing a frequency counter, and step S**104** of zeroing variables for a maximum peak signal received and maximum energy received. In step S**106**, a sound propagation timer is zeroed. In step S**108**, the controller **3350** communicates with a transmit driver **3330**, which communicates with the audio transmitter **3311** to generate audio emissions **3315**. For each frequency step, the controller **3350**, in step S**110**, samples an amplitude of the receive envelope detector **3364** and determines a maximum reflected energy off the target surface **3340**. In step S**112**, if a peak amplitude of the receive envelope detector **3364** is not greater than a maximum peak signal, the acoustic surface sensor **330**E proceeds to step S**120**, of decrementing the frequency counter. Otherwise, in step S**114**, the peak amplitude is stored as the peak amplitude of the current wavelength; in step S**116**, a maximum energy received is stored as the maximum energy received for the current wavelength; and in step S**118**, a determined target distance is stored. In step S**122**, if the frequency counter is zero, the acoustic surface sensor **330**E increments the frequency in step S**124** and loops back to step S**106**. If the frequency counter is not zero, the controller **3350**, in step S**126**, compares a maximum receive energy with a threshold energy to classify the surface as hard or soft.

Referring to FIG. **8**G, in some implementations, the receiver **3312** and optionally the transmitter **3311** are mounted with an anti-vibration mounting system **3370** in a manner that minimizes vibration transference from the housing **3310**. In the example shown, the receiver **3312** is secured with a high durometer rubber **3372** (e.g. Shore value of 70 A by the ASTM D2240-00 testing standard) in a tube **3374**. The tube **3374** is secured in the receiver receptacle **3314** with a low-durometer rubber **3376** (e.g. Shore value of 20 A by the ASTM D2240-00 testing standard). Sound absorbing foam **3378** is placed above the receiver **3312** in the tube **3374**. An adhesive **3779** (e.g. epoxy) may be used to secure leads **3380** from the receiver **3312** in the receiver receptacle **3314**.

Referring to FIGS. **1** and **9**, in some examples, the robot **10** includes a liquid detector **350** for detecting a liquid presence in its path. In one example, as shown in FIG. **1**, the liquid detector **350** is positioned toward the front of the body **100** to provide detection of a liquid quagmire before the drive system **400** contacts the potential obstacle. The liquid detector **350** aids the robot **10** in avoiding inadvertently falling into a body of water **1004**C (or losing traction therein). The liquid detector **350**, in some instances, includes two polarized light emitters **352**A and **352**B, respectively, and a polarized light detector **354**. The polarized light emitters **352**A and **352**B, respectively, emit mutually cross-polarized beams of light angled downward. The polarized light detector **354** is polarized with regard to one of the two light emitters **352**A, **352**B and positioned to detect whether a specular reflection has been removed from a generally quiescent surface of a liquid body **1004**C (e.g. water).

In some examples, the liquid detector **350** includes a sonic sensor, like the grass sensor **330** shown in FIG. **8**C, that emits a sonic signal and detects its echo. The liquid detector **350** discerns an echo characteristic of water **1004**C from an echo characteristic of grass **1020** or an otherwise non-water surface. Microwave or radar echoes may be used to discern the same characteristics. In other examples, the liquid detec-

tor **350** includes a capacitive or magnetic sensor which detects a shift in capacitance or magnetic field when proximal to water **1004**C.

Upon detecting a pond or other body of water **1004**C with the liquid detector **350**, the robot **10** performs a behavior consistent with obstacle or cliff avoidance. For example, the robot **10** alters its heading away from the detected body of water **1004**C, backs up, or issues an alarm.

Referring to FIGS. **10-22**, the robot **10** includes a cut edge detector **310** to determine an edge between uncut and cut grass, **22** and **24** respectively. In some implementations, cut edge sensing entails using a span of sensors **312** to recognize different grass types, growth rates, and other lawn properties. The cut edge detector **310** generally includes a span of sensors **312** extending into the uncut grass **22** to provide self-calibration or normalization for another span of sensors **312** intended to detect the edge between uncut and cut grass, **22** and **24** respectively. The cut edge sensing techniques employed in robot **10** may include combinations of rolling the cut grass **24** in front of the edge detector **310**, erecting the uncut grass **22** in front of the edge detector **310**, erecting the cut grass **22** behind the wheels **410**, **420**, **430**, **440**, behaviorally interpreting the cut edge **26** to robustly and smoothly follow the cut edge **26**, and disposing more than one cut edge detector **310** along the traveling length of the robotic mower **10**.

Referring to FIG. **10**, in some examples, the robot **10** includes an analog cut edge sensor **310**A to detect the mowed regions **24** and un-mowed regions **22** of a lawn **20** to ascertain the edge **26** defined therebetween. One example an analog cut edge sensor **310**A is provided in U.S. Pat. No. 4,887,415, the entire contents of which are incorporated by reference herein. The analog cut edge sensor **310**A includes metallic strips **69**, **70** and **71** aligned laterally, orthogonal to a forward direction of travel of the robot **10**, in which two of the metallic strips **69** and **70** project downward farther than the third metallic strip **71**. As the robot **10** proceeds forward while properly aligned to the cut edge **26**, the two larger metallic strips **69** and **70** contact the shorter grass of the previously mowed swath **23** in the cut area **22** while the shorter metallic strip **71** contacts the taller grass of the uncut area **22**. An electrical current passes from the shorter metallic strip **71** to the larger metallic strip **69** through moistened grass of the lawn **20**. Generally, recently cut grass of the mowed swath **23** will release moisture sufficient to permit electrical conduction. When no current passage from metallic strip **71** to metallic strip **69** is detected, the robot **10** determines that it has strayed from alignment with the cut edge **26** and may alter its heading until the current is once again detected, for example.

Referring to FIGS. **11**A-B, an alternative cut edge detector **310**B is exemplified in U.S. Pat. No. 5,528,888 which is incorporated by reference herein in its entirety. The cut edge detector **310**B may include a series of swing arms **80** that break electrical contact with a node **81** when the cut edge detector **310**B is in contact with sufficiently tall grass of the uncut area **22**. By positioning several swing arms **80** in a row in a comb-like fashion along a direction orthogonal to a forward direction of travel of the robot **10**, the cut edge detector **310**B can determine that the cut edge **26** lies between first and second adjacent swing arms **80**. The first swing arm **80** hits the tall uncut grass **22** and breaks contact with the node **81**, while the second swing arm **80** positioned over the shorter grass of the mowed swath **23** maintains contact with the node **81**. As otherwise discussed herein, this configuration may also use a calibration portion or sensor **320** separate from the cut edge detector **310**B.

Yet another example of a cut edge detector **310** includes a polarized light emitter, reflector, and detector system, as illustrated and disclosed in FIGS. 24-26 of U.S. Pat. No. 4,133,404, which is incorporated by reference herein in its entirety.

Other example cut edge detectors **310** for detecting the difference between the cut swath **23** and the uncut region **22** so as to determine the edge **26** therebetween include, but not limited to, an acoustic or piezoelectric sensor, an optical sensor, and a mechanical or electrical sensor system.

When an analog cut edge sensor **310** is employed, a calibrator **320** may also be included to provide a reference for calibration and comparison of the analog signal produced by the analog cut edge sensor **310**. In general, the calibration sensor **320** provides a reference signal against which the grass-trailing portion of the edge sensor **310** may be normalized or otherwise calibrated. In some examples, the calibration sensor **320** will trail in lawns **20** having essentially the same breed, health, height, moisture content or dryness, weed or clover content, debris/mulch content and character, stiffness, cut history, sparseness, and dumpiness (and other variability) as the lawn **20** being followed for edge sensing. The calibrator **320** may include a sensor element identical or similar to the cut edge sensor **310**.

The calibrator **320** may be positioned underneath, in front of, or behind the body **100**, so long as the position of the calibrator **320** relative to the body **100** is over the uncut grass area **22**. The calibrator **320** (as well as the analog cut edge sensor **310**, for example) may be mounted so as to minimize the chance of a damaging collision with rocks, debris, or other obstacles. In some examples, the calibrator **320** includes a rigid rock shield or hood mounted in front of the calibrator **320** to shield against collisions with debris larger than a clearance between the bottom of the rock shield and the ground **20**. Preferably, the cut edge detector **310** and the calibrator **320** are flexibly or pivotally mounted and/or floating at a certain height with respect to the ground **20** (e.g. by using a coupled wheel or skid to follow the ground **20** and/or moving together with a floating cutter **200** which may also employ a wheel or skid).

In many instances, the calibration sensor **320** is the same height as the cut edge detector **310**. In some examples, as shown in FIGS. **1-3**, the calibrator **320** is positioned on the body **100** in a location exposed to the tall grass of the uncut area **22**. Accordingly, when the calibrator **320** contacts the uncut area **22**, it provides a reference signal characteristic of uncut grass **22**. The robot **10** compares the signal provided from the cut edge detector **310** to the signal from the calibrator **320**. In some instances, the cut edge detector **310** includes an array of sensors **312** and generates multiple signals or one signal with multiple portions corresponding to each sensor **312** or different regions of the cut edge detector **310**. A signal or portion of the signal corresponding to a region of the cut edge detector **310** in contact with the uncut area **22** may substantially resemble a signal from the calibrator **320**. Conversely, a signal or portion of the signal corresponding to a region of the cut edge detector **310** exposed to a previously mowed swath **23** will substantially differ from a signal from the calibrator **320**. The heading of the robot **10** as it mows along the cut edge **26** is enhanced by continuously calibrating the cut edge detector **310** with the calibrator **320**.

One example calibrator **320** includes one or more optical sensors. The optical calibrator **320**A is a "break-beam" type sensor where a beam of infrared, visible, or other frequency of light emitted laterally toward a detector is interrupted with the presence of grass. Another example includes a

capacitive or static sensor as the calibrator **320**. In one instance, an electrical capacitance arising between an electrically charged conductor connected to the robot **10** and the grass of the uncut area **22** is detected. In another instance, static electricity generated by friction between the robot **10** and the tall grass of the uncut area **22** is detected. Other examples of calibrators **320** include sonar (which may be similar to the optical break-beam detector, substituting sound waves for light), acoustic (detecting noise indicative of tall grass as the robot **10** passes over it), displacement-to-magnetic, or any other sensor capable of indicating the difference between taller uncut grass **22** and shorter mowed grass **24**.

In some implementations, where the optical calibrator **320**A includes multiple optical sensors, the emitters and receivers of the optical sensors may include fiber optics, light pipes, multi-way reflectors and the like. In one example, a plurality of optical emitters may be replaced with a single emitter and an optical element that directs the emission in more than one direction. In another example, a plurality of optical detectors may be replaced with a single detector and an optical element that collects the emission from more than one direction. Conductive, capacitive, or electromagnetically resonant sensors may be combined, averaged, or weighted by connecting them to a conductive element or antenna. These sensors may use one sensor to collect signals from more than one location or direction. Multiple contact sensors responsive to vibration, such as microphones and piezoelectric elements, may be replaced by one or more members that conduct vibration to the sensor, and these also may use only one sensor to collect signals from more than one location or direction.

In some examples, high or distinctive frequencies of signals provided from the cut edge detector **310** and the calibrator **320** (e.g. optical, camera, vibration, acoustic, or other signal discussed herein) are processed or subject to transforms suitable for frequency domain analysis to characterize meaningful frequencies and to remove meaningless frequencies. For example, acoustic signals may be processed to remove or ignore both cyclic components and low frequency noise from motors, wheels, bearings, and/or cutters and identify "white noise" in the frequency range expected for blades of grass striking the detectors during forward movement of the robot **10**. Low-pixel camera, optical, and other signals may be processed similarly.

In some implementations, the type of sensor employed in the cut edge detector **310** and calibrator **330** are the same, in order to simplify the comparison of the calibration signal to the cut edge detector signal. However, these sensors **310**, **320** may be different and signal comparison is facilitated by normalization or conditioning of one or both of the signals.

Following an edge smoothly is somewhat analogous to following a wall smoothly. Once an appropriately conditioned signal is obtained, the robot **10** may perform signal interpretation and analysis and obstacle following algorithms, as disclosed in U.S. patent application Ser. No. 11/166,986, by Casey et al., filed Jun. 24, 2005 and titled OBSTACLE FOLLOWING SENSOR SCHEME FOR A MOBILE ROBOT, as well as U.S. Pat. No. 6,594,844; U.S. patent application Ser. Nos. 10/453,202; 09/768,773; and U.S. Provisional Application Nos. 60/582,992 and 60/177,703, all of which are incorporated by reference herein in their entireties. In this case, the "obstacle" or wall is the cut edge **26**. In addition to the edge following algorithm, in some examples, the robot **10** includes algorithms for determining or estimating the end of a row/swath **23** and turning to establish a new row while depending on the cut edge **26**.

FIG. **12** shows a rear schematic view of an example of a robot **10** including wheels **410**, **420**, a body **103**, a cut edge detector **310**, and a calibrator sensor array **320**. The cut edge detector **310** and the calibrator sensor array **320** each include a plurality or span of sensors, **312** and **322** respectively, projecting into the lawn **20**. The sensors **312** of the cut edge detector **310** project into the cut edge path **26**. In several instances, some of the sensors **312**, **322** may detect grass and some or all are positioned with respect to a cutting height (e.g. height of the cutter **200** and cutting blades) so that they do not detect cut grass **24**. The signals from multiple sensors **312** and **322** may be combined, averaged, filtered to provide one or more simple grass-no grass signals in digital form, or encoded (n bits of left-to-right grass/no-grass distribution).

Example arrangements of the plurality or span of sensors, **312**, **322** include lateral spans, front-to-back sets, and diagonal spans. Different arrangements provide different advantages in detecting grass and collecting averaged or cumulative data.

Referring to FIG. **13**, in some implementations, the robot **10** includes a cut edge detector **310**C having light sensors **380** mounted on struts **313** extending from a sensor mount **311**. The light sensor **380** includes an IR or visible light emitter **382** coupled with a receiver **384**. In some example, the emitter **382** and receiver **384** are angled toward an area of interest/distance of interest. The emitter **382** may be stepped up in power until reflected illumination is detected by the receiver **384**. Time of flight and/or phase measurements may be used to detect grass **20** in the area of interest. An active acoustic emitter and receiver may be used in a similar way, in addition detection echoes or the attenuation of echoes over time.

FIG. **14** shows an infrared (IR) sensor **390** including a light emitting diode (LED) **392** and phototransistor **394** pointed at and mounted opposite each other. Each is shielded from stray light by short black tubes **396** (e.g. heat-shrink tubing of about ⅛" i.d.). Light reaching the phototransistor **394** from the LED **392** is measured by synchronous detection, using cliff-sensor technology as discussed herein. This system can detect single or multiple grass blades with a vertical resolution of about ¼ inches. LED power levels, distance between IR emitter **392** and detector **394**, and diameter and length of the optical tubes **396** are all parameters that can be varied.

Referring to FIG. **15**A, in some implementations, the robot **10** includes a cut edge detector **310**D having emissive sensors **390** mounted on struts **313** extending from a sensor mount **311**. The emissive sensors **390** include an IR or visible light emitter **392** and receiver **394** positioned and aligned with each other such that an emission passes through an area or distance of interest. The receiver **394** may be configured to detect a partial or full obstruction. Time of flight or phase measurements may be used to detect grass in an area of interest. An active acoustic emitter and receiver may be used in a similar way.

Referring to FIG. **15**B, in some implementations, the robot **10** includes a cut edge detector **310**D having one or more front-to-back emitter-receiver sensor pairs **390**. In some instances, several emitter-receiver sensor pairs **390** arranged with a detection axis in a forward direction detect more grass than if arranged transverse to the forward direction. Each emitter-receiver sensor pair **390** may provide one bit or several bits. Multiple front-to-back sensor pairs **390** form a lateral array spanning the cut edge **26** to provide a signal for following the cut edge **26**.

In some implementations, each sensor **312**, **322** or sensor array **310**, **320** is arranged to rotate back or fold up and

return when the mower robot **10** encounters obstructions or obstacles at the height of the cutter **200** or above. In some instances, the mower robot **10** stops the cutter **200** from cutting when an obstruction has caused the sensor array **310**, **320** to flip or rotate upward.

Referring to FIG. **16**A, in some implementations, the robot **10** includes a cut edge detector **310**D having a sensor housing **3910** defining a cavity **3930** and a cavity opening **3932** configured to allow grass **22** entry while inhibiting direct sunlight **3990** into the cavity **3930**. The cavity **3930** may be colored a light absorbing color (e.g. black) or made of a light absorbing material. Grass **20** is inherently springy and may pop-up after deflection. The sensor housing **3910** is mounted to deflect uncut grass **22**, while passing over uncut grass **24**, as the robot **10** maneuvers across the lawn **20**. The sensor housing **3910** allows the deflected uncut grass **22** to self-straighten upward through the cavity opening **3932** and into the cavity **3930**. In some examples, the sensor housing **3910** is mounted to the body **100** at height relative to a ground surface that minimizes entrance of cut grass **24** the cavity **3930**. An emitter-receiver sensor pair **3900**, in communication with the controller **3350**, is carried by the housing **3910** and includes an IR or visible light emitter **3920** and receiver **3940** (e.g. photon detector). The emitter **3920** is positioned inside the cavity **3930** and configured to emit an emission **3922**A across the cavity opening **3932**. The receiver **3940** is positioned below the emitter **3920** and configured to receive a grass reflected emission **3922**B, while not receiving any direct sunlight **3990**. The receiver **3940** has a defined field of view that intersects a field of emission across the cavity opening **3932**. In preferred examples, the emitter-receiver sensor pair **3900** is arranged so that grass **20** below a certain height substantially does not reflect emissions **3922** back to the receiver **3940**.

Referring to FIGS. **16**B-C, in some implementations, the sensor housing **3910** is configured to carry an array of emitter-receiver sensor pairs **3900** (also referred to as grass height sensors) equally spaced apart and in communication with the controller **3350**. The sensor housing **3910** may be linear along a longitudinal axis **3911** defined by the horsing **3910** or curved and located on a forward portion of the body **100**. In some examples, dividers **3914** separate each emitter-receiver sensor pair **3900**. The array of grass height sensors **3900** may span the entire width or only a portion of the width of the body **100**. In some examples, a portion of the array of grass height sensors **3900** is used for the calibrator **320**. For example, one half of the array of grass height sensors **3900** provides edge detection, while the other half provides calibration. As the robot **10** travels forward, grass height estimates are acquired by the grass height sensors **3900** based on signal strength of the receiver **3940** from reflected emissions **3922**B. One example of measuring signal strength is turning the emitter **3920** off, measuring a first signal strength of the receiver **3940**, turning emitter **3920** on, measuring a second signal strength of the receiver **3940**, and obtaining a difference between the first and second signal strengths. The resulting difference in signal strengths is used for the sensor measurement (grass height signal) and generally has lower signal-to noise ratios. A grass height signal obtained by each grass height sensor **3900** is compared by the controller **3350** to a threshold value, above which grass is considered uncut and below which grass is considered cut, and stored as binary decisions in a grass height row vector **3905**, as shown in FIG. **16**C. Periodically, the controller **3350** compares the grass height row vector **3905** to previously stored exemplar row vectors **3905**B representative of ideal grass edge measurements at each sensor pair array position **3906** to determine a location of the cut edge **26** along the sensor array. With N number of grass height sensors **3900** in the array, there are (N−1) possible edge positions each having a stored exemplar row vector **3905**B, plus "no grass" and "all grass" stored exemplar row vectors **3905**B. The controller **3350** selects the exemplar row vector **3905**B (and corresponding grass edge array position) having the minimum number of differences (element by element) with the compared grass height row vector **3905** to determine the location of the cut edge **26** along the sensor array **310**D and therefore a cut edge position **26** under the body **100**. The number of differences with the selected exemplar row vector **3905**B is called the "grass edge clarity". The cut edge position and grass edge clarity may be used to influence the drive system **400** to create a grass edge following behavior.

The following example grass height vector Vx was acquired from an array of eight sensors **3900**. Vx=[0 1 0 0 1 1 1 0]

Table 1 below provides exemplar grass height vectors **3905**B and respective edge positions for an eight sensor array.

TABLE 1

Exemplar Grass Height Vectors	Edge position
[0 0 0 0 0 0 0 0]	0—no grass
[0 0 0 0 0 0 0 1]	1
[0 0 0 0 0 0 1 1]	2
[0 0 0 0 0 1 1 1]	3
[0 0 0 0 1 1 1 1]	4
[0 0 0 1 1 1 1 1]	5
[0 0 1 1 1 1 1 1]	6
[0 1 1 1 1 1 1 1]	7
[1 1 1 1 1 1 1 1]	8—all grass

Table 2 below provides the number of differences between the example grass height vector Vx and each exemplar grass height vector **3905**B.

TABLE 2

Exemplar Grass Height Vectors	Differences with V_x (Edge Clarity)
[0 0 0 0 0 0 0 0]	4
[0 0 0 0 0 0 0 1]	5
[0 0 0 0 0 0 1 1]	4
[0 0 0 0 0 1 1 1]	3
[0 0 0 0 1 1 1 1]	2
[0 0 0 1 1 1 1 1]	3
[0 0 1 1 1 1 1 1]	4
[0 1 1 1 1 1 1 1]	3
[1 1 1 1 1 1 1 1]	4

In the example above, the controller **3350** selects the exemplar row vector [0 0 0 0 1 1 1 1] (and corresponding grass edge array position of 4) as having the minimum number of differences (element by element) with the compared grass height row vector Vx. The fourth grass edge array position from a total of eight sensors **3390** is approximately the center of the detector **310**D.

Referring to FIG. **16**D, in some implementations, the use of a one dimensional vector **3905** for estimating a cut edge position and grass edge clarity is extended to a two dimensional model **3907** (e.g. a two-dimensional array) having a sliding window of M row vectors **3905** representing successive binary readings of the N grass height sensors **3900**. The number of row vectors **3905**, M, included in the two dimensional array **3907** depends on the frequency of measurements made over a distance, X, traveled by the robot **10** in a period of time, T. In one example, the sensors **3900**

measure grass height at a frequency of 512 Hz. A summation of differences between exemplar row vectors **3905**B and measured grass height row vectors **3905** is performed in the same manner described above, except on a row by row basis. The results of the compared rows may be averaged. In some examples, column data is summarized into a single summary row vector, where a row element **3906** is designated as "uncut" (e.g. by a corresponding 0 or 1) if any of the elements in that column contained an "uncut" designation.

Referring to FIG. **16**E, in some implementations, a peak grass height signal **3962** is determined for each sensor **3900** or a combination of sensors **3900** by combining grass height results from adjacent sensors **3900** (e.g. of 1-2 adjacent sensors **3900** on one or both sides of the sensor **3900**). The controller **3350** compares the peak grass height signals **3962** against stored threshold values, as described earlier, to determine if the grass is cut or uncut. In one example, the array of grass height sensors **3900** is divided into pairs of adjacent sensors **3900** and a peak grass height signal **3962** is determined for each pair of adjacent sensors **3900**. A grass height image **3960**, as shown in FIG. **16**E, is created depicting the peak grass height signals of the grass height sensors **3900** or combinations of sensors **3900**. The horizontal axis of the image represents the array of N grass height sensors **3900** and the vertical axis represents the number of measurements made within window of travel, X, by the robot within a period of time, T. Depending on the method of obtaining the peak grass height signals **3962**, each pixel **3964** may represent a peak (or avenge) value for a combination of sensors **3900** or only one sensor **3900** over a period of time. The pixel **3964** may have a color and/or intensity proportional to grass height signal strength. The controller **3350** compares an array of pixels (e.g. 4 pixels wide by 1 pixel high or 16 pixels wide by 16 pixels high) with one or more stored reference patterns (of the same array size) of different possible edge configurations. Different criteria may be employed in matching reference patterns with sample arrays to determine the location of the cut edge **26**. With pattern matching, the controller **3350** can determine the orientation of the cut edge **26** with respect to the robot **10**. For example, while searching for a cut edge **26** to follow, the robot **10** can determine an approach angle when encountering a cut edge **26** based on the orientation of the orientation of the cut edge **26** with respect to the robot **10**. In the example shown in FIG. **16**E, the darker pixels **3964**A represent weaker the peak grass height signals **3962** characteristic of cut grass **24** and the lighter pixels **3964**B represent stronger the peak grass height signals **3962** characteristic of uncut grass **22**. The boundary between the lighter and darker pixels **3962** provides the estimated location of the cut edge **26**. In this particular example, the robot **10**, while executing an edge following behavior, mannered left and right to follow the cut edge **26**, hence the vertical zig-zag appearance. As an energy saving technique, the robot **10** may turn off the cutters **200** to save power while detecting all cut grass **24** and then turn the cutters **200** on again once uncut grass **22** is detected.

The drive system **400** maneuvers the robot **10** while keeping the grass edge **26** centered in the array of grass height sensors **3900** of the cut edge detector **310**D. In one implementation, the drive system **400**, configured as a differential drive and at least one passive front caster, in one example, uses the determined grass edge **26** to steer the robot **10** by selecting a turn radius. The further left the determined grass edge **26** is of the center of the array of grass height sensors **3900**, the shorter left turning radius selected by the drive system **400**. The further right the determined grass edge **26** is of the center of the array of grass height sensors **3900**, the shorter the right turning radius selected by the drive system **400**. The turn radius is proportional to an error in edge placement (i.e. location of the cut edge **26** with respect to the center of the robot **10**.) In another implementation, when the determined grass edge **26** is left or right of the center of the array of grass height sensors **3900**, the drive system **400** turns the robot **10** left or right, respectively, as sharply as possible while keeping both left and right drive wheels **410** and **420**, respectively, moving forward. The drive system **400** drives the robot **10** straight when the determined grass edge **26** is centered on the array of grass height sensors **3900**.

Several robotic behaviors are employed to achieve mowing coverage of the lawn **20**. In some implementations, the behaviors are executed serially (versus concurrently). The highest priority behavior is a perimeter following behavior. While creating the perimeter following behavior, the robot **10** follows a perimeter through bump sensing or the use of confinement devices (e.g. boundary responders **600**). This tends to create cut grass edges **26** around obstacles and property perimeters that can later be followed using a cut edge following behavior. The next highest priority behavior is cut edge following. The cut edge following behavior uses the grass edge position as estimated by the grass edge sensor array **310**D to control the heading of the robot **10**. The grass edge following behavior creates a new cut edge **26** behind the robot **10** that closely matches the contour of the edge **26** it was following. The next highest priority behavior is a tall grass turn behavior, which is executed after the robot **10** detects all uncut grass as estimated by the grass sensor array **310**D for a predetermined amount of time, such as five seconds. Using only dead reckoning, the robot **10** performs a tight turn to bring the grass edge sensor array **310**D back into the grass edge **26** just cut by the robot mower **10**. The robot **10** may maintain a history of the cut edge sensing to allow approximations of the location of the last detected at edge **26**. The robot **10** may also drive in a random direction or pattern (e.g. spiral) to find a cut edge **26**. The tall grass turn behavior is designed to avoid fragmentation of the lawn **20** into many islands of uncut grass **22** that need to be found through random traverses rather than through methodical cutting by following a grass edge **26**.

Referring to FIG. **17**, in some implementations, the robot **10** includes a cut edge detector **310**E having a flap **302** of sufficiently flexible material to which the sensors **312**, **322** are secured. The sensors **312**, **322** move together with the flap **302** when an obstruction is encountered. The sensors **312**, **322** are arranged to precede the cutting head **200** in a direction of mower robot **10** at a height at or near the cutting height. In some examples, the sensors **312**, **322** include microphones (alone or attached to strips of material), piezoelectric transducers, conductors, capacitors, or excited transducers with damped or interfered wavelengths. Each detector or transducer **312**, **322** is arranged such that a disturbance by contact with a blade or clump of grass is detectable (by movement, vibration, bending, conductivity, capacitance). The detectors **312**, **322** may be isolated from the supporting continuous flap **302** or able to detect disturbances of the flap **302** (which may provide an averaged signal). In some cases, only a protruding tip of the detector **312**, **322** may be sensitive (e.g., for piezoelectric material excited by bending).

Referring to FIG. **18**, in some implementations, the robot **10** includes a cut edge detector **310**F having multiple sensors **312** extending downward from a sensor mount **311** and including a vibration (or signal) sensor **315** mounted to a

sensor probe **313** (i.e. signal or vibration conductors). The sensors **312** are arranged such that a disturbance by contact with a blade or clump of grass is detectable (by movement, vibration, bending, conductivity, capacitance). The flexibility and/or drape of the probes **313** may be similar to string, chain, bristles, or stiff pins, and may be selected to dampen, attenuate or filter vibrations detrimental to the detection of uncut grass **22**. The length of the probe **313** serves to transmit the vibration or signal to the signal sensor **315**, and in some cases, to attenuate, damp, or filter the signal or vibration. In one example, a piezoelectric strip sensor **312**A includes a strip of thin piezo film **315**A deposited on a Mylar substrate **313**A (or individual strips mounted to individual struts **313**). The sensor **312**A is mounted to allow deflection by blades of grass, or deflection by a moving finger in contact with the blades of grass. The sensor **312**A produces a voltage output when mechanically deflected that is proportional to the amount and rate-of-change of deflection. The sensor output may be subject to signal filtering and amplification.

Alternatively, a lightweight detector member may be rotatably mounted to a potentiometer, hall sensor, mechanical switch, or optical encoder (reflective or transmissive photo-interrupter) that measures detector member rotation from encountered grass in an amount proportional to grass density, height, thickness, etc.

Referring to FIG. **19**, in some implementations, the robot **10** includes a cut edge detector **310**G having a vibration (or signal) sensor **315** mounted on a continuous contact flap **303**. The flexibility of the flap **303** may be similar to a thin plastic sheet, metal foil, or sheet metal, and may be selected to dampen, attenuate or filter vibrations detrimental to the detection of uncut grass **22** as well as to average multiple signals conducted by the flap **303**. Examples of the vibration (or signal) sensor **315** include a microphone, a piezoelectric transducer, a conductive sensor, a capacitive sensor, and an exciting transducer. Resonating or standing waves geminated by the flap **303** may be dampened or subject to interference with the exciting transducer separate from a detection transducer. The vibration (or signal) sensor **315** is configured to detect flap disturbances by movement, vibration, bending, conductivity, capacitance, etc. (e.g. from contact with a series of blades or clumps of grass). The edge sensor configuration shown in FIG. **18** captures contacts across the width of the flap **303**.

Referring to FIG. **20**, in some implementations, the robot **10** includes a cut edge detector **310**H and calibrator **320**B carried by the body **103**. The cut edge detector **310**H is a crenellated flap **303**A with separate flap portions **304** providing either separation or flexibility to isolate, dampen, attenuate or filter vibrations or other conducted signals detrimental to the detection of uncut grass **22**. The separate calibration array **320**B trailing in the uncut grass **22** provides a signal for normalizing or continuously calibrating a grass detection signal provided by the cut edge detector **310**H. In the example illustrated, the calibrator **320**B includes a first crenellated flap **303**A and a second relatively longer crenellated flap **303**B. The second relatively longer crenellated flap **303**B detects a complete lack of grass (e.g., as a secondary or complementary grass sensor **330**).

Multiple sensors **312**, **322** may be placed into the grass **20** (e.g. with probes **313** or flaps **303**) at different heights, e.g., in crenellated, staircase, or other stepped fashion, to provide additional information and resolution. In some instances, the sensors **312**, **322** are actuated upward and downward by a motor or linkage to measure obstruction, reflection, or conducted signal (including sound) at different heights. In some additional instances, the sensors **312**, **322** (and all of or a subset of the associated struts, probes, sensors, or flaps) are actuated upward and downward by a motor or linkage to follow a grass height as detected or as predicted.

Referring to FIGS. **21-22**, in some implementations, a rotating cut edge detector **310**I, rotating in a horizontal or vertical plane, replaces multiple sensors **312**, **322** and increases a signal frequency. For conductive sensors, a rotating cut edge detector **310**I, rotating in a horizontal plane, may be used. The rotating cut edge detector **310**I includes a rotating disk **316** configured with protrusions/spokes **317** or slots/depressions **318** which rotate with the disk **316** to increase the frequency and intensity of contacts with the grass **20**. The size of the rotating disk **316** determines the averaged area for a signal, and different disk sizes may be used in different locations on the robot **10**. Alternatively, the same disk size may be used in situations in which the disk size controls the resonant frequency, capacitance, or other size-dependant property. In some examples, a disk height is adjustable (e.g. via a motor or links) according to grass height, or increased/decreased periodically. The signal provided is characteristic of grass rubbing against, contacting, or striking the disk **316**. For example, the signal may be characteristic of acoustics, vibrations, or mechanical resistance (to rotation) from the grass **20**. The rotating cut edge detector **310**I provides signal readings while the robot **10** is stationary as well.

The cut edge detector **310**, in some implementations, resolves the cut edge **26** down to about plus or minus an inch horizontally, ½ inch preferably, and resolves the cut edge **26** down to about plus or minus ½" height, ¼" preferably. In some examples, the cut edge detector **310** detects an edge **26** when approaching from a first direction between about 30-90 degrees to a second direction normal to the cut edge **26**. In other examples, the cut edge detector **310** detects the edge **26** when approaching from between about 0-30 degrees from a direction normal to the cut edge **26**.

In some implementations, the robot **10** includes a substantially horizontally oriented forward sensing boundary sensor **340**. In some instances, a reflection type sensor as shown and described herein with reference to FIG. **13** is used. In other instances, the boundary sensor **340** is a camera or passive reception sensor. In many cases, the cliff detection sensor would be of analogous type. The boundary sensor **340** detects, for example, flowers, bushes, and fragile flexible structures not detectable by a depressible bumper soon enough to prevent damage. In some instances, the boundary sensor **340** is configured similarly to the multi-frequency color-based grass sensor **330** described earlier. The boundary sensor **340** may be filtered, shuttered, partially covered, or the signal therefrom conditioned, to emphasize vertical and diagonal lines typical of plant stalks and trunks.

FIG. **23**A is a schematic view of a lawn care robot system **5** including a robot **10** and boundary responders **600**. Boundary responders **600** placed on or in the ground **20** constrain or influence a behavior of the robot **10**. In some implementations, the autonomous robot **10** includes a boundary responder emitter-receiver unit **1500** including a signal emitter **1510** which continuously or periodically emits a signal (e.g. a radio-frequency, electro-magnetic wave, or an acoustic signal) and a signal receiver **1520**. In other implementations, the emitter **1510** is not necessary with certain kinds of active or semi-active boundary responder **600**. Examples of boundary responders **600** include passive resonant boundary responders and powered active radio-frequency identification (RFID) boundary responders. Passive boundary responders echo or generate a responsive signal to

a signal emitted from the robot **10** that is detected by the signal receiver **1520**. Passive resonant boundary responders are detected by measuring the energy transferred from the emitter **1510** operating at a resonant frequency. Each of the boundary responders **600** discussed may be structured to drape well, in the manner of loose chain with a small bend radius (e.g., less than 2 inches, preferably less than 1 inch). In some examples, active boundary responders **600** are only powered when the robot **10** is within a certain range.

When the robot **10** approaches and detects a boundary responder **600**, the robot **10** initiates a responsive behavior such as altering its heading (e.g. bouncing back away from the boundary responder **600**) or following along the boundary responder **600**. The boundary responder **600**, in some examples, passively responds to a signal emitted by the signal emitter **1510** of the robot **10** and does not require a connection to a central power source such as an AC power outlet or origin dock. In other examples, the boundary responder **600** is a powered perimeter wire **6012** that responds to a signal emitted by the signal emitter **1510** of the robot **10**. The powered perimeter wire **600** may be connected to a central power source such as an AC power outlet or origin dock. The powered perimeter wire **6012** may also be provided on a spool and cut to length for application. The powered perimeter wire **600** may also be provided in pre-cut length for application having connectors at each end of the pre-cut wire. In some implementations, passive and active boundary responders **600** are both detected by the same robot antenna **1520**.

Referring to FIG. **23**B, in some implementations, the signal emitter **1510** is a circuit **1514** including an antennae loop **1512** configured as a figure-eight, which creates a null in the antennae loop **1512** to prevent ringing and minimizes transmitted signal coupling into the receiver antennae **1522** thereby allowing earlier detection of a received pulse in the time domain. The signal receiver **1520** is a circuit **1524** including an antennae loop **1522** surrounding and coplanar with the antennae figure eight loop **1512** of the signal emitter **1510**. The figure-eight antennae loop **1512** coplanar with the receiver antennae loop **1522** provide increased detection range for the same amount of transmitting power over conventional coplanar antennae loops. An emitter-receiver control unit **1515** controls the signal emitter **1510** and receiver **1520** and communicates with the drive system **400**. The emitter-receiver control circuit **1515** activates the signal emitter **1510** for a period of time. The signal emitter **1510** emits a radio frequency (RF) signal (e.g. at 13.56 MHz) to passive boundary responders **600** tuned to the transmitted frequency. Inductive and/or capacitive circuits **620** in the passive boundary responders **600** absorb the RF energy and re-radiate the energy back to the signal receiver **1520** (e.g. at a frequency other than 13.56 MHz). The re-radiate signal will persist for a period of time after the signal emitter **1510** has ceased emissions. The detected signal is processed by the emitter-receiver control unit **1515** and communicates a boundary responder presence to the drive system **400**. Depending on the type of boundary responder **600**, the drive system **400** may direct the robot **10** away, over, or to follow the boundary responder **600**.

Referring to FIG. **24**, a boundary responder **600** includes a boundary responder body **610** having one or more inductive and/or capacitive circuits **620** (herein termed "tank circuits"). The tank circuits **620** may be formed, deposited, or printed on the boundary responder body **610**. For example, the tank circuits **620** may be formed on the boundary responder body **610** by photolithography, in a manner similar to silicon integrated circuit manufacturing; printed onto the boundary responder body **610** using ink jet or other depositional techniques; or manufactured individually and affixed to the boundary responder body **610**. The tank circuits **620** may include localized compact folded/concentric loops, or loops extending along the length of the cord or tape body **610**A. Although the boundary responder **600** is shown as a flat tape with printed circuits, the circuits **620** may include longer concentric, spiraled or other antenna-like elements, and may be constructed in a tape-like form wound or rolled into a cord-like or wire-like form.

In some examples, the boundary responder **600** has a predictable resonance frequency by having the boundary responder body **610** formed as a continuous cord or web with discrete inductive/tank circuit elements **620** of a known responsive frequency.

In general, tank circuits **620** are known and used in different arts. For example, low frequency versions are placed to facilitate the detection of buried cables (e.g., 3M Electronic Segment System, U.S. Pat. Nos. 4,767,237; 5,017,415), trapped miners (U.S. Pat. No. 4,163,977), or swallowed radioendosondes (e.g., the Heidelberg capsule), such as U.S. Pat. Nos. 6,300,737; 6,465,982; 6,586,908; 6,885,912; 6,850,024; 6,615,108; WO 2003/065140, all of which are expressly incorporated herein by reference in their entireties. When tank circuits **620** are exposed to a magnetic pulse or electromagnetic energy at a particular frequency they will ring for a time at a frequency determined by the capacitor and inductor. Each tank circuits **620** may be tuned to the same frequency, in some examples, and for better discrimination tuned to two or more different frequencies, in other examples. In some implementations, the robot **10** pulses a transmitter **1510** and looks for a response from the tank circuits **620** of the boundary responders **600**. In other implementations, the robot **10** sweeps a transmitting frequency and looks for a response at each particular frequency. Certain types of receiving coils for the signal receiver **1520** (a figure-8 coil, for example) can detect a phase shift as an external tank circuit **620** passes a centerline of the coil, allowing the robot **10** to detect when it crosses the boundary responder **600**. In some examples, a receiving coil or antenna of the signal receiver **1520** and the tank circuits **620** of the boundary responders **600** are disposed in parallel planes.

In some implementations, the boundary responder **600** includes amorphous metal, which may remain passive but emit a responsive signal when it receives an electromagnetic signal. When the boundary responder **600** composed of amorphous metal (either entirely or partially) receives an electromagnetic signal, for example, the amorphous metal becomes saturated and emits a spectrum of electromagnetic signals, including harmonic frequencies of the received incoming electromagnetic signal. Amorphous metal requires very little magnetic field to become saturated. When an amorphous metal is exposed to even weak RF energy the metal goes into and out of magnetic saturation during each cycle. This provides a non-linearity in the metal's response to the radiation and results in the production of harmonics to a fundamental frequency. This property is quite rare in normal environments. In some implementations, to detect a boundary responder **600**, the robot **10** generates a signal (e.g. modulated frequency) to excite any nearby amorphous metal which will radiate harmonics of the transmitted frequency. The robot **10** detects the harmonics of the radiated frequency (using synchronous detection, for example) to determine a locality with respect to the boundary responder **600**.

In some examples, the emitter **1510** of the robot **10** emits an electromagnetic signal as it traverses a yard **20**. Upon

approaching a boundary responder **600**, the boundary responder **600** receives the electromagnetic signal from the robot **10** and emits a responsive signal including harmonics of the received electromagnetic signal. The signal receiver **1520** of the robot **10** receives and analyzes the responsive electromagnetic signal using a circuit or algorithm. The robot **10** then performs a predetermined behavior (such as turning away from or following the boundary responder **600**, as appropriate).

A wire-like or tape-like boundary responder **600** including at least one portion composed of amorphous metal does not need a tank circuit **620**, thereby reducing manufacturing costs. When the boundary responders **600** includes tank circuits **620** or is composed of amorphous metal (or both), the boundary responders **600** may be cut to length (at fixed or variable intervals), curved, bent, or otherwise manipulated for placement on or beneath the yard **20**. The boundary responders **600** may be supplied on a spool or reel, for example, and cut with scissors or garden shears into segments of a particular length. The boundary responder **600** is affixed to the yard **20** by a number of methods, including, for example, placing it beneath thick grass; adhering it to the ground **20** using lime, concrete, epoxy, resin, or other adhesive (e.g., when traversing pavement such as a driveway or sidewalk), tacking it down with lawn nails or stakes, or burying it up to an effective depth of soil such that the boundary responder **600** can still detect and respond to incoming signals.

The boundary responder **600** is severable or separable at and between the circuits **620**. Cutting boundary responders **600** made of amorphous metal or having many tank circuits **620** about its entire length does not destroy the ability of the boundary responder **600** to detect and respond to incoming signals. If one tank circuit is **620** is damaged during cutting, other tank circuits **620** located elsewhere along the boundary responder body **610** will still function properly. When amorphous metal is cut, its electromagnetic properties remain generally unchanged.

Referring to FIG. **25**, a boundary responder **600**A, in some examples, includes a circuit **620**A having has one or more pairs of conductors (e.g. parallel wires) shorted together to form an inductor loop **622**. Load circuits **624** may set a resonant frequency. In some implementations, the narrow (e.g. ⅜") wire loop **622** is constructed of parallel wires (e.g. 300-ohm twin lead) with the ends shorted to create a loop inductor capable of resonating at an appropriate wavelength (e.g., 100 MHz). Twin-lead is available in many forms, including antenna tape and invisible twin lead (thin wires bonded to sticky tape). Although FIG. **24** shows spaces between the circuits **620**A (which may be marked with "cut here" indicia of any kind), the boundary responder **600**A, in some examples, includes a boundary responder body **610** having continuous twin leads **622**. Shorting shunts placed along the responder body **610** at fixed intervals (e.g. 1 to 6 feet) creates repeating circuits **620**A. The boundary responder **600**A is severable or separable at the shunts between circuits **620**A. The shunts may include loading inductors or capacitors to make resonance less dependent on length.

Orientation of the detection antenna **1520** on the robot **10** may be appropriate to detect the circuits **620**. The detection antenna **1520** may be provided in a rotating loop or as three orthogonally arranged impedance balanced antennae components, which detects energy absorption by the resonant circuit **620** at a known frequency. The configuration depicted in FIG. **24** can power active RFID-type components.

Referring to FIG. **26**, a boundary responder **600**B, in some examples, includes spiral or multi-loop conductors **622** with optionally attached loading elements (capacitor, inductor) **624**. In cases where longer circuit loops **620** are used, e.g. 1-6 foot long inductive loops, the boundary responders **600** may be severed at marked places **626** (e.g. perforations) between adjacent circuit loops **620**. In each case, the loading elements **624** are optional.

FIG. **27** shows a boundary responder **600**C including a boundary responder body **610** formed of multiple laminae **630**. Each lamina **630** includes printed, deposited, or etched loading elements **624** (capacitor, inductor) and/or loop inductors **622**, or parts thereof. Some of the structures **622**, **624** may be completed by lamination of the entire responder body **610** (e.g. parts of the loading elements and/or loops being distributed among different laminae). The lamina **630** may be single sheets of Mylar with a deposited shaped layer or metal foil etched to a desired shape.

FIGS. **28** and **37** depict a boundary responder **600**D including a circuit **620**D arranged within a responder body **610**D formed as a spike or tack. In some examples, the responder body spike **610**D includes a responder top **612** visible above the ground **20**. In some examples, the responder top **612** is passively excitable, e.g., fluorescing and detectable by the not-grass detector **330**. The responder top **612** is a flag in some examples with loading elements **624** placed in a flagpole. In some examples, the boundary responder **600**D is connected to an extended loop inductor **622** or extended antenna, with or without loading elements **624** in the responder body spike **610**D or flagpoles. The boundary responder **600**D may be connected to one another to form a stand. If loading elements **24** are in the responder body spikes **610**D, the resonance may be dominated by the loading elements **24**, but an extending antenna **622** can distribute the length of the circuit responsive to resonance between periodically placed boundary responders **600**D. In some examples, the tank circuit **620** of the boundary responders **600** are disposed in a head portion of the responder body **610**D (e.g. to position the tank circuit **620** in a plane parallel to the signal receiver **1520** of the robot **10**).

Referring to FIG. **29**, in non-passive examples, a boundary responder **600**E includes RFID emitters **625** in place of loading elements **624** and emitting a signal detectable by the signal receiver **1520** of the robot **10** and a loop **622**E. The RFID tag **525** receives a signal transmitted by the signal emitter **1510** of the robot **10** and replies by broadcasting stored information. In some examples, the boundary responder **600**E includes a power source (e.g. battery) to extend a range of the boundary responder **600**E (e.g. the robot **10** could detect the boundary **600**E at a greater distance).

In some implementations, the boundary responder **600** includes one or more acoustic devices which chirp when remotely excited to establish a boundary. In other implementations, the boundary responder **600** emits and/or receives visible-spectrum signals (color codes or other encoded message passing, for example) via retro-reflectors or optical targets. Optical targets are distinguishable from other objects in a visual field of the robot **10**. The optical targets may be printed with a "self-similar" retro-reflective pattern illuminable with modulated illumination. The optical targets may identify endpoints of the boundary responder **600**.

In one example, a boundary responder **600**F includes a magnetically chargeable loop **622**F. A moving (e.g. rotating) magnet carried by the robot **10** transfers energy. For example, a magnet is placed on a moving part of the cutter

200 (e.g. a spinning blade, or oscillating shears). The boundary responder 600F is installed in or on the ground 20 with the loop 622 orientated to derive sufficient flux through the loop 622. The material of the rotating or reciprocating support for the magnet or magnets should not short out the lines of flux (e.g., plastic or non-conductors). In some examples, the magnetically chargeable loop 622F is used to wakeup a battery powered continuous loop 622D.

In another variation, a boundary responder 600G includes a plastic cable body 610G with fluorescence embedded therein or painted thereon, activatable with a UV radiating source (e.g. LED) on the robot 10 and severable to any length. The fluorescence boundary responder 600G, in some examples, is masked or embedded to encode (e.g. long, short, long) a responder kind. In still another variation, a boundary responder 600H includes a quarter or half-wave antenna or inductor-loaded antenna, detectable by resonance, re-radiation, or energy absorption in a similar fashion to the tank circuits 620 previously discussed herein. Again, different frequencies may be detected. If the boundary responder 600H is cut to length, a first pass by the robot 10 establishes a frequency to be expected on that particular lawn 20. In still another variation, a boundary responder 600I includes a flat responder body 610I defining rumble strips vibrationally or acoustically detected and preferably arranged with distinctive periodicity to generate distinct frequencies for detection.

FIG. 30 provides a schematic view of a property 1001 with a property interior 1001A having a house 1002 surrounded by cuttable areas 1020 (e.g. a grassy lawn 20), grass-cutting obstacles 1004 (e.g. trees 1004A, bushes 1004B, and water 1004C, and immovable objects 1004D), boundaries 1006 (e.g. fences 1006A and property lines 1006B), and non-cuttable areas 1008 (e.g. driveways 1008A, sidewalks 1008B, and roads 1008C, and flowers/garden 1008D).

Referring to FIG. 31, an example mower system installation for a property 1001 includes arranging boundary responders 600 along the length of a neighboring property line 1006B. There is no particular need to arrange segments along the sidewalks 1008B or street 100BC, as these will be detected as described herein. The flower bed 1008D, which is both fragile and difficult to detect, is also protected with a boundary responder 600. The remainder of the obstacles 1004, 1006 in the property 1001 are detected by a sensor suite of the robot 10 as described herein. In this case, most of the lawn 1020 is contiguous with a few areas bounded by pavement 1008B. The mower robot 10 can be lead to the bounded areas or provided with a behavior that follows boundary responders 600 to the bounded areas. For example, a behavior may direct the robot 10 to follow the boundary responders 600 across pavement or mulch 1008 with the cutter 200 turned off, but not across a drop or cliff. A cliff sensor suitable for detecting such cliffs or drops is disclosed in U.S. Pat. No. 6,594,844 and incorporated by reference herein in its entirety.

Referring to FIG. 32, in some examples, multiple types of boundary responders 600 exist. Boundary responders 600 including resonant circuits 620 (whether using lumped or distributed inductance and capacitance) may have different resonant frequencies to convey boundary type information. In one example, a passive boundary responder 6010 signals the robot 10 to maneuver over it and whether mowing should start, continue, or halt. The passive boundary responder 6010 may also trigger the robot 10 to perform other actions upon detection. For example, a follow type boundary responder 6010A signals the robot 10 to follow the responder 6010A for its entire length (e.g., to cross a driveway or navigate a long dirt or pavement path between zones). In another example, an enter type boundary responder 6010B signals the robot 10 to enter an area normally off-limits (e.g., to navigate along a sidewalk to get from front to rear yards or to continue cutting across a path of separated flagstones). In yet another example, upon detecting a do not enter type boundary responder 6010C, the robot 10 initiates a behavior to alter its heading to bounce back away from the boundary responder 6010C.

In some implementations, the powered perimeter wire 6012 and the passive boundary responders 6010A-C both operate at the same frequency (e.g. at 13.56 MHz). The powered perimeter wire 6012 has a duty cycle, alternating between powered and un-powered, to not overshadow signals from passive boundary responders 6010A-C located on a property 1001 circumscribed by the powered perimeter wire 6012. When the powered perimeter wire 6012 is quiet, the signal receiver 1520 can detect passive boundary responders 6010A-C. The duty cycle is set to allow the robot 10 to quickly alternate monitoring of active responder 6012 and passive responder 6010A-C confinement while maneuvering across the lawn 1020.

After installation of the boundary responders 600, the robot 10 may traverse the property 1001 without any cutters 200 activated to check the placement of boundary responders 600. In some instances, the robot 10 is configured to operate only when within a certain range of the boundary responders 600 or when the boundary responders 600 are active (e.g. for safety purposes). For example, the robot 10 is configured to detect a current direction in boundary responders 600 powered with alternating current to determine whether it is inside or outside of a boundary perimeter. Other techniques of preventing robot escapes include using GPS to determine a robot location, determining a distance from a beacon, and using virtual walls including beacons that emit an emission (e.g. infrared light or radio frequency) detectable by the robot 10. In some examples, the robot 10 employs proximity detection to protect against moving into people or pets. A radio frequency identification tag (RFID) recognizable by the robot 10 may be placed on people or pets to prevent their collision with the robot 10.

Robot navigation components may be divided into five sub-categories: follow cut grass edge (i.e. find the boundary between the cut and uncut grass); stay on the grass (i.e. passive grass/not-grass detection); stay within the arbitrary boundaries (i.e. don't cut the neighbor's lawn); don't stray too far (e.g. backup/secondary system); and end near a specified location. The backup system, for example, may be a radio-based detector restricting the robot 10 from traveling too far from a home base (which would be optionally integrated with a battery charging device). Some implementations include using a GPS circuit, determining a signal strength of the responder 600, or resolving a time of flight from a local encoded beacon. As a security and/or safety measure, the robot 10, in some examples, may not operate other than within a restricted coordinate set, or absent an appropriate signal. To minimize error and signal loss from weather, canopy or obstacles, the robot 10 may be trained with the signal characteristics of the property 1001 (e.g. the first full cycle of mowing the lawn would collect baseline signal data for determining minimum and maximum thresholds of the property 1001). This provision may also be overridden by the user with appropriate authorization. A beacon or GPS signal may aid the robot 10 in returning to

an end location specified by the user, or an additional short or mid-range radio or visible beacon provided for homing purposes.

U.S. Pat. No. 6,690,134 by Jones et al., entitled Method and System for Robot Localization and Confinement, the entire disclosure of which is herein incorporated by reference it its entirety, discloses methods for confining and localizing an indoor robot using directed IR beams and multi-directional sensors; and U.S. Provisional Patent Application No. 60/741,442, "Robot Networking, Theming, and Communication System," filed Dec. 2, 2005, which is herein incorporated by reference in its entirety, discloses additional methods for chamber-to-chamber localization, confinement, and navigation using different frequencies and ranges of IR beams and multi-directional sensors. These can be used as, in combination with, or instead of, the boundary responders **600** discussed herein. Although the use of IR beams and detectors is less effective outdoors, various implementations may use higher wavelengths of IR emission and detection (e.g., 900 nm+). The IR emission and detection may be baffled, channeled, and filtered to remove sunlight and/or sunlight spectral components. The IR emission and detection may also be modulated to permit AC coupling on receivers to reject daylight and other steady light sources. Narrow beam (5 degrees or less) microwave (e.g., in conventional radar gun/detector frequencies) emitters and detectors can be used instead of, or in addition to, directed IR beams (complementary false positive rejection) with the same interpreting software and behaviors.

Referring to FIG. **33**, in some examples, the mower robot **10** includes one or more tilt sensors **710** (e.g. accelerometers) monitoring a robot tilt to avoid mowing or maneuvering above a maximum robot tilt angle. The tilt sensor **710** may also provide terrain data that aids robot maneuvering and behaviors. For example, when the tilt sensor detects a robot tilt, the robot **10** compares a measured robot inclination with known values to determine whether it is maneuvering over a threshold, tree roots, humps, hillocks, small hills, or other surface phenomena that may be treated as obstacles, but not easily detectable by bumpers or proximity sensors.

In some examples, the mower robot **10** includes a rain sensor, such that it returns to a home base when rain is detected.

The robot **10** includes at least one stasis detector **442**, in some examples, such as an idle wheel sensor (e.g., optical, magnetic, limit switch encoder on non-driven wheels) or a drive wheel torque/current sensor for detecting a stuck condition. The cut edge sensor **310** or edge calibration sensor **320** is used as a stasis sensor in some cases, or as a backup sensor for a wheel torque/current sensor type stasis sensor. Any camera, including optical mouse-type or other low-pixel cameras, even when used for other purposes (e.g., grass/no grass), can be used as a stasis sensor when no movement is detected. In some cases, a motor load of the cutter **200** is monitored for a stasis or stuck condition. Any combination of these can be interpreted as a stuck condition when the circumstances giving rise to that response are appropriate (e.g., no grass detected+no cutting load=stuck, unless front wheel is rotating and motor load is normal).

In some implementations, the robot **10** includes additional obstacle detectors such as bump, infrared, optical, sonic, and horizontal-scanning sensors for detecting collision hazards (i.e. chain-link fences) within a path of the robot **10**. In one example, a horizontally oriented sonic sensor is capable of detecting a flower pot or tree trunk prior to a collision, enabling the robot **10** to alter its heading to avoid the obstacle.

In some examples, the robot **10** includes a clipping collector **720**, such as a sack or barrel for collecting grass clippings or yard debris. The clipping collector **720** includes a capacity sensor **722**, in one implementation. Examples of the capacity sensor **722** include an acoustic sensor that analyzes an acoustic spectral response of a substantially rigid clipping barrel and a break-beam optical sensor. The break-beam optical sensor has an emitter projecting a beam of light across the clipping collector to a receiver. When the beam of light is not detected by the receiver, the robot **10** determines that the clipping collector **720** is full and performs an appropriate behavior such as ceasing mowing, or dumping the contents of the clipping collector **720** at a designated location, for example.

In some examples, the robot **10** communicates wirelessly with a remote monitor, also discussed interchangeably herein as a wireless remote able to communicate with transceiver **55** on the robot. The remote monitor is a small console or indicator, in some instances, not significantly larger than 3 cubic inches. The remote monitor may be affixed to a refrigerator door or other metal object using a magnet. The remote monitor signals to an operator that the robot **10** needs assistance when the robot **10** becomes stuck, damaged, unsafe for operation, or unable to empty the clipping collector, for example. The remote monitor may include a kill switch to terminate operation of the robot **10**; and/or may transmit a dead-man signal without which the robot **10** will not operate. In one example, the robot **10** sends a radio-frequency signal via an unlicensed frequency (e.g. 900 MHz or 2.4 GHz) to the remote monitor. The wireless signal may encode information via frequency or amplitude modulation, for example, and/or via any appropriate communications standard such as Bluetooth, ZigBee, WiFi, IEEE 802.11a, b, g, n, wireless USB (UWB), or a proprietary protocol such as discussed in U.S. Provisional Patent Application No. 60/741,442, "Robot Networking, Theming, and Communication System."

A base station acts as a relay or intermediary, in some instances, between the robot **10** and the remote monitor. In some examples, the base station includes a charging system and communicates with a wired or wireless home network. The remote monitor sounds an audible alarm (particularly if the signal issued by the robot indicated that a dangerous condition or accident had occurred) and/or flashing light or other signal, for example, to bring a robot distress condition to the attention of an operator. The remote monitor may communicate data transmitted by the robot **10** on a display (e.g. LCD) or via a voice synthesizer. Examples of transmitted data include area of lawn mowed, remaining power level, and warning alarms.

A base station and an autonomous robot configured for autonomously docking and recharging is specifically described in U.S. patent application Ser. No. 10/762,219, by Cohen, et al., filed on Jan. 21, 2004, entitled Autonomous Robot Auto-Docking and Energy Management Systems and Methods, the entire disclosure of which is herein incorporated by reference it its entirety. User input commands, functions, and components used for scheduling a mowing cycle directly on the robot **10** or via the base station and/or any boundary responders **600** are specifically described in U.S. patent application Ser. No. 11/166,891, by Dubrovsky et al., filed on Jun. 24, 2005, entitled Remote Control

Scheduler and Method for Autonomous Robotic Device, the entire disclosure of which is herein incorporated by reference it its entirety.

In some implementations, the robot **10** mows a swath **23** having a generally spiral path, combined with boundary following, edge following, and random movement. Spiral spot cleaning essentially equivalent to spiral mowing as well as wall following essentially equivalent to obstacle and/or boundary responder following are specifically described in U.S. Pat. No. 6,809,490, by Jones et al., entitled, Method and System for Multi-Mode Coverage for an Autonomous Robot, the entire disclosure of which is herein incorporated by reference it its entirety.

The robot **10** may have a single dominant following side **101**, **102**, or let one side **101**, **102** dominate depending on whether a boundary **600**, **1004**, **1006**, **1008** or cut edge **26** is to be followed. Boundary responders **600** may be followed differently from physical boundaries, e.g., on the robot edge, the cut edge, or the robot center. When the cutting head **200** extends fully across one side **101**, **102** of the robot body **100** but not the other, either side **101**, **102** of the robot **10** may still be a dominant and/or boundary following side. The robot **10** follows obstacles **1004**, **1006**, **1008** on the side **101**,**102** having greatest cutter extension to cut as close to an edge as possible, yet may still follow cut edges **26** on the other side **101**, **102**.

Alternatively, the robot **10** may follow both cut edges **26** and boundaries **600**, **1004**, **1006**, **1008** on the same side **101**, **102** with an asymmetrical blade arrangement **200**. An asymmetrical cutter **200** leaves an uncut spot, e.g., where the cutting head **200** is offset to the right and the robot **10** spirals to the left, the bottom portion of the robot **10** with no cutting head coverage creates a small uncut circle in the center of the spiral. This can be addressed by adding to the spiral a center pass based on dead reckoning, or by following the spiral with one or two center pass figure-eights based on dead reckoning, or by reversing the direction of the spiral.

FIG. **34** provides a schematic view of an alternative non-random coverage pattern **3000** by the robot **10**. The pattern **3000** is suitable for robots **10** having offset and non-offset cutting heads **200**. To make the pattern **3000**, the robot **10** follows a succession of offset overlapping loops **3005**, such as those traversed by Zamboni® ice resurfacing machines. A general wheel path **3010** is shown in dotted lines and a general coverage path **3020** is shown in solid lines. The overlap is sufficient to cover any uncut spots caused by the offset cutting head **200** or offset differential drive system **400**. The pattern **3000**, in one example, includes as a series of overlapping rounded-corned rectangles achieved by right-angle differentially steered turns. In other examples, the pattern **3000** includes smooth ovals. A distance across each loop **3005** of the pattern **3000** can be any size. Larger loops **3005** incorporating many substantially straight lines provide greater cutting efficiency than smaller loops **3005**. However, drift error may accumulate with large loops **3005**, disrupting the pattern **3000**. If the loops **3005** are too small, too much time is spent turning. A cutting quality during turning may not be as satisfactory as while cruising straight. A balance of cutting performance, speed, and loop size may be established for each yard **20**. In one example, the loop **3005** is sized to completely cover a center of the loop **3005** on a third to sixth parallel pass (parallel whether the loop **3005** is irregular, circular, oval, square, or rectangular) and overlaps by no more than half of a cutting width on each pass. Example patterns **3000** include loops **3005** overlapping by about 120%-200% of a distance **107** from a wheel center to an edge of the cutting head **200**, loops **3005** offset by a cutting width **108** minus about 120%-200% of distance **107**, loops **3005** overlapping by about ⅕-⅓ of the cutting head width **108**, and loops **3005** offset by about ⅘-⅔ of the cutting head width **108**, having loops **3005** less than three to four times as wide as the yard **20**. In many instances, the loops **3005** are substantially symmetrical. The pattern **3000** is adjusted to leave no gaps in the cut area **22** for a robot **10** cutting to a following or dominant side edge **101**, **102**, or having a cutter **200** that does not extend to the edge on either side **101**, **102**.

With any cutting path, it is not critical that the rows are straight, but more important that the robot follows its previous pass/swath **23**. The reference swath **23** may be parallel to a curved or stepped obstacle. Following previous swaths **23** improves efficiency, as compared to random bouncing (reducing time on the working surface from 5× deterministic to 1.5-3 times deterministic), and improves a user's perception of the robot's effectiveness and aesthetics of the lawn **20**.

A method of mowing a yard includes placing an autonomous mower robot **10** in a yard **20** and allowing the robot **10** to mow a reference row/swath **23** of arbitrary or boundary-constrained length. The robot **10** proceeds to follow a cut edge **26** of the reference row/swath **23**. At the end of the reference row **23**, the robot **10** turns and row follows for each successive row **23**, mowing a pattern **3000** as described above. The pattern **3000** has successive offset overlapping loops **3005** that spiral and increase in size with each iterative loop **3005**. The robot **10** continues mowing by following the cut edge **26** of a preceding row **23** until an arbitrary area has been cut or the pattern **3000** is interrupted by an obstacle **1004** or boundary **1006**. The robot **10** then moves to a new uncut area **24** of lawn **20** (randomly or using collected boundary history), mows a new reference row **23**, and repeats the mowing process until the lawn **20** is estimated to be complete. The robot **10** uses a reference heading from a navigational system to establish each reference row **23**, the edge of which is followed to mow substantially parallel rows.

In addition to or in lieu of the cut edge sensor **310**, in some example, the robot **10** includes one or more auxiliary navigational systems to enhance alignment and navigation of the robot **10**. For example, the robot **10** may include a global positioning satellite (GPS) receiver, a radio signal time-of-flight sensor, an inertial guidance system including one or more accelerometers or gyroscopes, or an optical landmark sensor. Any single positional system may suffer drift or continuously decreasing precision during operation. Multiple positional systems enhance navigational precision.

In one example, the robot **10** includes an electronic compass that returns a heading accurate to about +/−6 degrees. In another example, the robot **10** includes an odometer. In yet another example, the robot **10** includes a global positioning satellite (GPS) receiver, which provides a heading within a few degrees accuracy after traveling tens of meters in a straight line. By integrating the input from two or more heading systems the heading precision can be improved (for example, in accordance with any of the techniques set forth in U.S. Patent Application "Mobile Robot Autonomous Navigational and Obstacle-Avoidance System," filed Dec. 30, 2005, inventor Brian YAMAUCHI, the contents of which are incorporated herein by reference in their entirety). For instance, after mowing a 100 meter swath **23**, the robot **10** turns approximately 180 degrees to start a new swath **23** and obtains a first heading vector from the GPS receiver. The GPS may render a degree of error of about plus or minus 6 degrees. The robot **10** obtains a second

heading vector from an electronic compass and compares the two heading vectors to determine an averaged heading to follow.

If, for example, it is desired to approximate rows/swaths **23**, the robot **10** may obtain assistance from the heading. Rows/swaths **23** may be made parallel by edge following or without edge following by a heading vector. Alternatively, the rows/swaths **23** may be slightly open and zig-zagged, e.g., opening by a degree amount larger than the heading error every turn. The rows/swaths **23** may alternate parallel rows with closed-angle rows, e.g., crossing back to redo a likely cut area **22** by either more than the heading error or less than the row width every turn. Each row/swath **23** is arranged to successively advance the mowed area **22**.

In one example, a hybrid compass/odometry localization technique is used to determine a robot position. The compass is used to determine a robot orientation and odometry is used to determine a distance translated between updates. The robot position is determined using the following equations:

$$\Delta_t=\sqrt{(x_t-x_{t-1})^2+(y_t-y_{t-1})^2}$$

$$x'_t=\Delta_t \cos \theta_t$$

$$y'_t=\Delta_t \sin \theta_t$$

where (xt, yt) is the odometry position at time t, θt is the compass heading at time t, Δt is the distance traversed between time t−1 and time t, and (x't, y't) is the hybrid compass/odometry position estimate for time t.

Odometry tends to accumulate error. Over a single traverse of the lawn **20**, odometry may accumulate over 90 degrees of orientation error, for example. In contrast, a compass in conjunction with odometry enables the robot **10** to determine the robot position within a few degrees. The hybrid compass/odometry localization method may determine a robot position accurately to within a few meters after a circuit of the lawn **20**. The inclusion of one to three axes of accelerometer data increases accuracy as well. Any combination of odometry, compass, GPS, or inertial guidance may be processed by a Kalman filter if sufficient computation capacity is available.

In examples using GPS, inertial or odometric guidance, landmark recognition and/or other dead reckoning or navigational sensors, the robot **10** can determine whether it has crossed a boundary **1006**, **1008** into a road, or onto a neighbor's property, for example, and take appropriate corrective action (such as shutting down or navigating back to a home point or recognized landmark).

The robot **10** may align its initial row or each set of rows using a preferred heading. From row **23** to row **23**, the robot **10** may use corrected heading data to avoid drift and maintain an appearance of successive rows. The robot **10** may use the corrected heading data to locate new areas to mow as well.

Referring to FIGS. **35**A-D, as discussed above, the robot system **5** may use a combination of active boundary wire **6012** and passive guard barriers **6010**. The robot system may be provided with splice and/or terminator connectors **5910** for moving, rerouting, or repairing the active boundary **6012**. A typical rearrangement is shown in FIG. **35**A, where a user has elected not to mow a driveway **1008**A but instead reroutes the active boundary **6012** using two splice connectors **5910**. The splice connectors **5910** may butt-splice or side-by-side splice a single or dual conductor, and are preferably tool-less snap-closed connectors that include a blade that penetrates insulation and connects the wires **6012**. The splice connectors **5910** may also be terminators, e.g., terminating a dual-conductor length to become a loop. The splice connectors **5910** may be used to connect wire **6012** provided as discrete lengths. An example splice connectors **5910** is shown in FIG. **35**B. As shown in FIG. **35**A, the entire active perimeter **6012** may be a combination of wire lengths and splice connectors **5910** (not excluding other devices which may be placed along the perimeter). In some cases, the splice connectors **5910** may be provided with test circuits useful for checking the position of a break in the boundary (e.g., if each splice connector includes a socket, conductor loops can be tested by connecting adjacent splice connectors using a test line with a detector (e.g., lamp), or by plugging in a test lamp at subsequent splice connectors).

FIGS. **35**A and **35**C, depicts robot-activated power stations **5912** placed along the active perimeter **6012**. The robot-activated power stations **5912** may be battery and/or solar powered, which may in some cases permit isolated lengths to be used or a main extension **5920** from household AC to the powered perimeter boundary **6012** to be avoided. Some power stations **5912** may include an emitter, receiver, or antenna, as well as control. The robot **10**, in this case, is provided with an emitter **1510** that "excites" nearby power stations **5912**. For example, the robot **10** may be provided with an RF or IR emitter **1510** of limited range that only activates ("wakes up") a power station **5912** when the robot **10** is in a certain range. The excitation range may be longer than the distance between any two to four power stations **5912**. After a power station **5912** is activated, it may hand-shake with the robot **10** over the receiver channel using its own emitter or over another channel for communication (e.g., line-of-sight such as collimated or omnidirectional visible light or IR) to ensure that a neighbor's power stations, for example, are not activated. Implementations that activate a limited portion anywhere along an entire perimeter **6012** (e.g., a sector or sub-portion of the entire boundary including two to four power stations) only when the robot **10** approaches the perimeter **6012**, allow the boundary **6012** to be battery powered and/or use smaller batteries. The power stations **5912** may be placed along, and bridge, single conductor or dual conductor perimeters **6012**. In the case of dual conductors, any two power stations **5912** or power station **5912** and terminator may close a circuit formed by the dual conductors.

FIG. **35** shows an anchor **5930**. An anchor **5930** may be a beacon including a primary non-line of sight emitter of limited signal strength and may include a secondary line of sight or directional emitter as well. When the robot **10** travels outside the signal strength limit of the anchor **5930**, it may deactivate or may seek the anchor using the secondary emitter. A virtual anchor may be provided using terrestrial navigation signals, e.g., GPS. A robot **10** provided with a global positioning (GPS) receiver may be locked to a position approximately within the center of the yard to be cared for or mowed. Although commercial GPS typically has insufficient resolution to provide a useful location within most yards and is not reliable under canopy or other natural barriers. GPS can provide sufficient resolution to determine that the robot **10** is no longer close to an anchor point **5930**. A controller **452** on the robot **10** may deactivate the robot **10** when it is sufficiently far (e.g., 100 feet) from its anchor point **5930**; and may also activate an anti-theft claxon, radio beacon, lockout, or other countermeasure when the robot **10** is very far (e.g., greater than 200 yards) from its anchor point **5930**.

FIGS. **36-38** depicts a typical use of passive "spike" type guard barriers **600**D. As shown in FIG. **36**, the no-go boundary type passive spikes **6010**C may be arranged to

surround an area that would not be detected by hard surface, boundary, bump, or other detections. The spikes **600**D are placed at from one half to two robot working widths from one another, depending on the antenna **1520** and emitter **1510** configuration of the robot **10**. The spikes **600**D may be used in conjunction with the splice connector **5910**-type boundary or power station **5912** type boundary of FIG. **35**. As shown in FIG. **37**, each spike **600**D may include an RFID or tank circuit disposed on a horizontal thumbtack-type head. The head **612** prevents the spike **600**D from being pushed too far (more than 3-5 inches for a spike of corresponding length) into the ground and burying the circuit **620** to be detected. The perpendicular orientation of the spike-head circuit **620** permits arranging the antenna or circuit **620** in the best orientation (e.g., parallel) to be excited and/or detected by an antenna **1510** on the robot **10**. The head **612** may be provided with hooks or holes **612**A formed therein for using a line to check the distance between spikes. Optionally, each spike or some spikes may be provided with a flag **612**B (e.g., "corner" spikes with a different resonant frequency or encoding, and used in corners, may be the only ones provided with small flags).

Spikes **600**D may be easier to install if they are provided with an installation tool **5950**. The tool **5950** may be a "spiking tool" approximately 36 to 48 inches in height (i.e., the approximate height or lower of a typical user's hip) and may be provided with a handle **5952** at the top and a stirrup **5954** at the bottom. In use, a spike **600**D may be placed in the tool **5950** (either manually in a slot or loaded from the top of the tool **5950** to fall into a receiving mechanism at the bottom). Then the tool **5950** is arranged to insert the spike **600**D in the earth. The stirrup **5954** permits the user to use his or her weight to force the spike **600**D into the ground. A measuring line **5956** may hang from the tool **5950**, and the measuring line **5956** may be hooked or fixed to a last-placed adjacent spike **5950** to set a distance from spike to spike. The tool **5950** may also be provided with a clamp or levering mechanism to more easily close the splice connectors previously mentioned. The shaft extending from the handle **5952** to the stirrup **5954** may include a telescoping, folding, or other compacting mechanism to permit the tool **5950** to stow in a smaller size. In this case, the clamp or levering mechanism may be arranged for use with the tool **5950** in the smaller size.

A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. For example, the robot may be used without a network. The network may be used without a robot. A different mobility platform may be provided for the robot. No one (or more) element or feature described is implicitly, explicitly, or inherently critical or necessary to the operation of the robot or lawn care system, except as explicitly described herein. Although several sensor arrangements have been described as detecting grass along a lateral line substantially perpendicular to the direction of forward movement, the sensor orientation itself may be front to back or diagonal. Although reference has been made to lawn-mowing and/or shrub-trimming robots, it is nonetheless understood that any of the features set forth also apply to any lawn care autonomous robot. Accordingly, other implementations are within the scope of the following claims.

What is claimed is:

1. A method performed by an autonomous robot lawnmower for cutting grass, the method comprising:

following a path defined by one or more responders, an end of the path being in a second area, thereby crossing a first area between the second area and a third area, to move autonomously from the third area to the second area without cutting grass in the first area;

determining that the autonomous robot lawnmower has reached the end of the path and is inside of a perimeter of the second area based on detecting the one or more responders; and

cutting grass within the second area upon determining that the autonomous robot lawnmower is inside of the perimeter of the second area.

2. The method of claim **1**, further comprising: cutting grass within the third area before following the path.

3. The method of claim **1**, further comprising disabling a grass cutter of the autonomous robot lawnmower before following the path.

4. The method of claim **3**, further comprising enabling the grass cutter before cutting grass within the second area.

5. The method of claim **3**, further comprising: enabling the grass cutter while the autonomous robot lawnmower is inside of a perimeter of the third area.

6. The method of claim **3**, further comprising: enabling the grass cutter while the autonomous robot lawnmower is within a prescribed range of at least one of the one or more responders.

7. The method of claim **1**, further comprising: detecting, using a stasis detector carried by the autonomous robot lawnmower, stasis of the autonomous robot lawnmower.

8. The method of claim **7**, wherein the stasis detector comprises an optical sensor.

9. The method of claim **8**, wherein the optical sensor is a mouse-type sensor.

10. A method performed by an autonomous robot lawnmower for cutting grass, the method comprising:

following one or more responders along a path, the path having an end in the a cuttable area, to cross a non-cuttable area, thereby autonomously moving from a second cuttable area to the first cuttable area while a grass cutter of the autonomous robot lawnmower is disabled;

enabling the grass cutter when the autonomous robot lawnmower reaches the end of the path and is inside of a perimeter of the first cuttable area based on detecting the one or more responders; and then

cutting grass within the first cuttable area.

11. The method of claim **10**, further comprising: cutting grass within the second cuttable area before autonomously crossing the non-cuttable area.

12. The method of claim **10**, further comprising: autonomously disabling the grass cutter of the autonomous robot lawnmower before autonomously crossing the non-cuttable area.

13. The method of claim **10**, wherein the grass cutter is enabled when the autonomous robot lawnmower is within a prescribed range of at least one of the one or more responders.

14. The method of claim **10**, further comprising: detecting, using a stasis detector of the autonomous robot lawnmower, stasis of the autonomous robot lawnmower.

15. The method of claim **14**, wherein the stasis detector comprises an optical sensor.

16. The method of claim **15**, wherein the optical sensor is a mouse-type sensor.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,713,302 B2
APPLICATION NO. : 14/489847
DATED : July 25, 2017
INVENTOR(S) : Paul E. Sandin et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims

Column 48, Line 37, in Claim 10, delete “the a” and insert -- a first --, therefor.

Signed and Sealed this
Twenty-sixth Day of September, 2017

Joseph Matal

Joseph Matal
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office